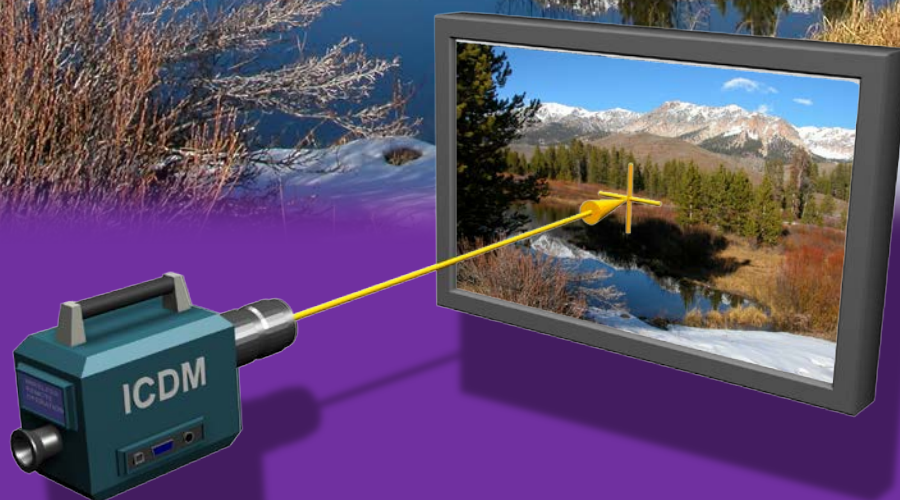




INFORMATION DISPLAY MEASUREMENTS STANDARD



INTERNATIONAL COMMITTEE FOR DISPLAY METROLOGY

IDMS

SID

SOCIETY FOR INFORMATION DISPLAY

Definitions and Standards Committee

International Committee for Display Metrology (ICDM)



www.sid.org/Standards/ICDM

INFORMATION DISPLAY MEASUREMENTS STANDARD

VERSION 1.2

May 2023

Abstract: This document consists of standard measurement procedures to quantify electronic display characteristics and qualities. However, it is also a document that discusses display metrology or the science of display measurements in that it reveals some of the problems associated with making display measurements, contains diagnostics to reveal those problems, and offers solutions to these measurement difficulties. In general, we avoid setting any performance criteria or performance minima. The hope is to serve standards organizations that wish to minimize the amount of space dedicated to measurement descriptions and make reference to this document instead. Consider the measurements in this document to be a buffet from which the desired measurement methods can be selected depending upon the needs of the user.

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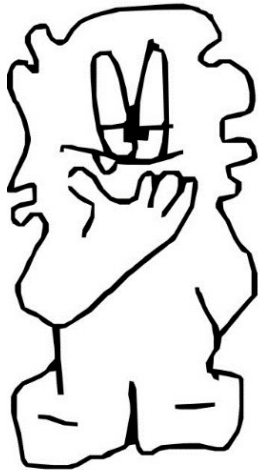
(This page is intentionally left blank.)



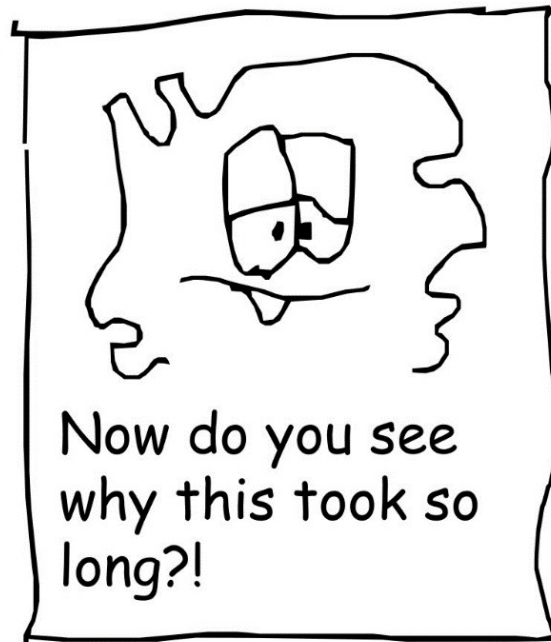
This is not a blank page.
Somebody put "This
page..." at the top, so it
isn't blank after all.



Can we call a non-
blank page a blank
page in a standards
document?!



Maybe we should
label it some other
way?



Now do you see
why this took so
long?!

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Look! A footer.
Indeed, it isn't
blank.

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1. Introduction

This document (IDMS, Information Display Measurements Standard) is the work of the International Committee for Display Metrology (ICDM) under the Definitions and Standards Committee of the Society for Information Display (SID). Please visit <https://www.sid.org/Standards/ICDM> for current information. This document is provided to detail various measurement *methods* to characterize electronic displays. (From here on we will simply refer to them as “displays” and not add the term “electronic.”) It is an accomplishment of a world-wide effort from many contributors (see Appendix F for acknowledgments). The goal is to express good display metrology in an unambiguous manner, to offer diagnostics and warnings when things can go wrong, to present measurement methods clearly and in a self-contained manner, and to present those measurements in a buffet form to be selected as needed. An important intention of this document is that we hope to relieve other standards organizations the burden of writing extensive measurement procedures with all the appropriate warnings and required conditions of proper implementation.

This is not a compliance document; we do not tell you what you should get for results; we tell you how to get the results in a reliable, reproducible, and robust manner as much as possible. (A measurement method is robust if reproducibility can be achieved easily, and the measurement result is not sensitive to small parameter changes in the apparatus used to make the measurement.) Other standards organizations are interested in compliance to specified value ranges. In general, we are only interested in the proper measurement of a display characteristic. In rare instances we may offer suggestions on how the measurement results can be considered from a vision-science or ergonomics viewpoint, but our focus is on the measurement method.

1.1 Philosophy and structure

There are several issues that help to define the philosophy and structure of this document. We have employed setup icons to remove some of the redundancy that normally accompanies measurement methods and that are usually obvious to the experienced person. They are identified fully in chapter 3, Setup of Display & Apparatus.

1.1.1 Intellectual property

The IDMS is a display measurement and metrology standard to help evaluate displays by providing many measurements, techniques for subjective evaluation, and appendices with helpful references. It may be downloaded without charge provided the user accepts and agrees to the Terms of the Society for Information Display End User License Agreement. Revised versions of the document will be posted at <https://www.sid.org/Standards/ICDM> when they become available; updates and support material will also be found as they develop.

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1.1.2 Initial acronyms and definitions

The word “screen” is used throughout this document to mean the active visible area that produces video information—often called the viewable area of the screen or display. The *diagonal* of the screen refers only to the diagonal measure of the *viewable area* of the screen, assumed to be rectangular. The term “diagonal” may not be used to refer to parts of the surface of the display that either do not contain image producing pixels or are covered by a bezel in normal operation of the display. Most of the methods in this document apply to *direct-view* displays as opposed to virtual displays, although projection and head mounted displays are covered where noted (see for example, chapter 19, Near Eye Displays). Displays that emit light (can be seen in a darkroom) are referred to as *emissive* displays in this document and include liquid-crystal displays (LCDs) that often are referred to by their pixel



properties as transmissive displays. Now that there are actual transmissive displays—displays that you can see through—and not just transmissive pixels, the use of “transmissive” may be more restrictive in the future. Displays that are *reflective* modulate reflected light whereby ambient light is required to view the information. *Transflective* displays exhibit both emissive (transmissive pixels) and reflective properties.

There are several acronyms that are used throughout this document that are identified here. Individual chapters may have their own special acronyms used locally in that chapter.

TABLE 1.1. Acronyms used in IDMS.

CCT	Correlated color temperature	LMD	Light-measurement device or detector
CRT	Cathode ray tube	MTF	Modulation transfer function
DOI	Digital object identifier (<a href="https://doi.org/<DOI>">https://doi.org/<DOI>)	OLED	Organic LED
DUT	Display under test	PLED	Polymer LED
DVD	Digital video disk or digital versatile disk	PDP	Plasma display panel
FPD	Flat panel display	RGB	Red, green, blue (color primaries)
FPDM	Flat Panel Display Measurements Standard (VESA)	CMY	Cyan, magenta, yellow
FHD	Full high definition, 1920×1080	WK	White and black
HD	High definition, 1280 × 720	RMS	Root mean square
ICDM	International Committee for Display Metrology	SID	Society for Information Display
IDMS	Information Display Measurements Standard (this document)	SLET	Stray-light-elimination tube
IR	Infrared (radiation)	TV	Television
JND	Just-noticeable difference	UHD	Ultra-high definition, see Rec. ITU-R BT.2020-2
LCD	Liquid crystal display	UV	Ultraviolet (radiation)
LED	Light-emitting diode	VESA	Video Electronics Standards Association

1.1.3 IDMS compliance

The only compliance that can be associated with this document is compliance with the measurement procedures, methods, analysis, reporting requirements, etc. This document does *not* set compliance values for any of its measurements—that is the job of other standards organizations. For any measurement result expressed in any reporting documentation, *i.e.*, a specification sheet, to claim compliance with the ICDM IDMS *must* mean that the measurement method used to obtain that result and any restraints on reporting are compliant with the method(s), procedure(s), and documentation specified in this document. Any exception or deviation (see 1.1.6) in the method or apparatus configurations must be clearly stated in any reporting documentation. Please be honest.

1.1.4 Buffet

The philosophy of this document is simple. We want to provide to the display industry with a variety of measurement methods to quantify display performance and quality. We provide detailed procedures and try to forewarn you about any problems with the measurement method or equipment. The format is as a *buffet* where you pick what you want to eat; here, you choose what measurements you need to make—not every measurement needs to be made. Some methods are similar to other methods but yield different results. It is up to you or somebody directing you to pick what measurement result is needed. We do provide some examples of reporting templates in chapter 2 (Templates, Composites, and Suites) for your consideration and use.

1.1.5 Hierarchy

There are various ways to group the measurement methods into major divisions. We have tried to accommodate the display-industry usage and familiarity as of this writing. The major divisions attempt to emphasize what is currently important to the industry. We have also tried to avoid several layers of hierarchy so the document will be readable and easy to navigate. Some measurement methods can be placed in several different sections. Thus, the uniformity



chapter could include a measurement of uniformity of viewing angle, or the viewing angle chapter could similarly include the same method as well.

1.1.6 Exceptions and deviations

The results of these measurements and calculations will be reported in some form of documentation. We use the term “reporting documentation” (or a similar form) in this document to include *any* form of reporting, be it verbal, printed, electronic, etc. Sometimes exceptions and deviations from the methods specified in this document will be encountered or desired to meet your needs. Any exceptions or deviations from this document must be recorded and noted in any reporting documentation of the measurement results. If we must change the settings on the display to properly characterize it for a particular application, then that modification of the setup or method *must* be clearly stated in any reporting documentation. For example, an automobile manufacturer may want to know the dimming range of the display, which will mean that the display settings will have to be changed to characterize the display for this automotive use.

1.1.7 Examples, sample data, and configuration examples

Note that examples or sample data are often provided in the measurement sections. These are not intended to be goals, suggested levels, or suggested measurement results. They are simply examples to show how results might be reported or to provide a calculation check for the reader. We often show various detectors and displays as examples of the measurement implementation. In the figures throughout this document, we show various instruments. In Figure 1.1 we show a spectroradiometer (or luminance meter), array detector, video generator, irradiance meter (or illuminance meter), *etc.* In presenting these figures, we have not intended to show any preference to the make any manufacturer of any equipment employed. Any resemblance to existing or future equipment is accidental, and our making these figures does not suggest endorsement of any particular instrumentation.



FIGURE 1.1. Examples of light measurement devices

1.2 Colorimetry, photometry, and radiometry

Throughout the document we will speak of measurements of luminance and color. The color space referred to is often the 1931 CIE color space based upon X , Y , Z tristimulus values and the corresponding chromaticity coordinates x , y ,



and z . This is presently the fundamental basis for other color spaces in use. Should other color spaces be required now or in the future, then consider the 1931 CIE color space used in this document to represent a placeholder for these other color spaces as is needed. We encourage the use of more relevant color spaces such as CIELAB, and future ones as they are perfected. In addition, the measurement procedures and metrics described in this document generally apply to display systems in which the input signals conform to a standard set of RGB voltages or digital values; any deviations need to be fully documented to all interested parties.

Please understand, when we speak of making a luminance measurement or a color measurement, we do not preclude making a radiometric measurement of the spectral radiance that will provide both the luminance and color measurement. Similarly for an illuminance measurement, a spectral irradiance measurement will provide more information than a simple illuminance measurement. Radiometric measurements are more general measurements and can be more useful in understanding the light from a display.

For example, in chapter 5 (Fundamental Metrics) we state to “Measure the luminance and optionally the chromaticity coordinates” of a simple pattern. Equivalently, we could measure the radiance of the full-screen pattern and calculate the luminance and chromaticity coordinates, and we could derive the color coordinates for any color space we needed. Thus, it is understood that we will refer to luminance, illuminance, *etc.*, and chromaticity coordinates, but we could equivalently make radiometric measurements throughout this document. Some methods will require making radiometric measurements, and we will clearly indicate such requirements. However, in general, we will refer to luminance (photometric) and color (colorimetric) measurements with the understanding that radiometric measurements can include these results and provide more information.

1.3 Updates, changes, addenda, and correlations

Several modifications will be continuously needed to maintain this document between major releases. Users of this document need immediate access to these changes.

1.3.1 Updates

The display industry is rapidly changing, and new measurement methods continue to be needed. Also, in a document this large there are bound to be errors. Please visit www.sid.org/Standards/ICDM#8271482-idms-changelog to find any listing of errors or any updates that are required.

1.3.2 Addenda

A variety of items are available in connection with this document at <https://www.sid.org/Standards/ICDM>. This includes patterns, templates, spreadsheets, *etc.* These will continue to be included as the ICDM effort extends.

1.3.3 Changes

As the document matures, all changes from one version to another will be documented in Appendix G.

1.3.4 Correlations with other standards

For correlations with other standards documents, also see Appendix G. This listing will be updated as more available standards are reviewed by our contributors.



This page was intentionally left without important information content.

Well, doesn't that
depend upon what
you call important?



Good point! I think
it's important to
know the page is
blank.



But the page
isn't blank!



Well, then, why
don't we define a
blank page in the
glossary?!!

Now do you
see why this
got so big?!

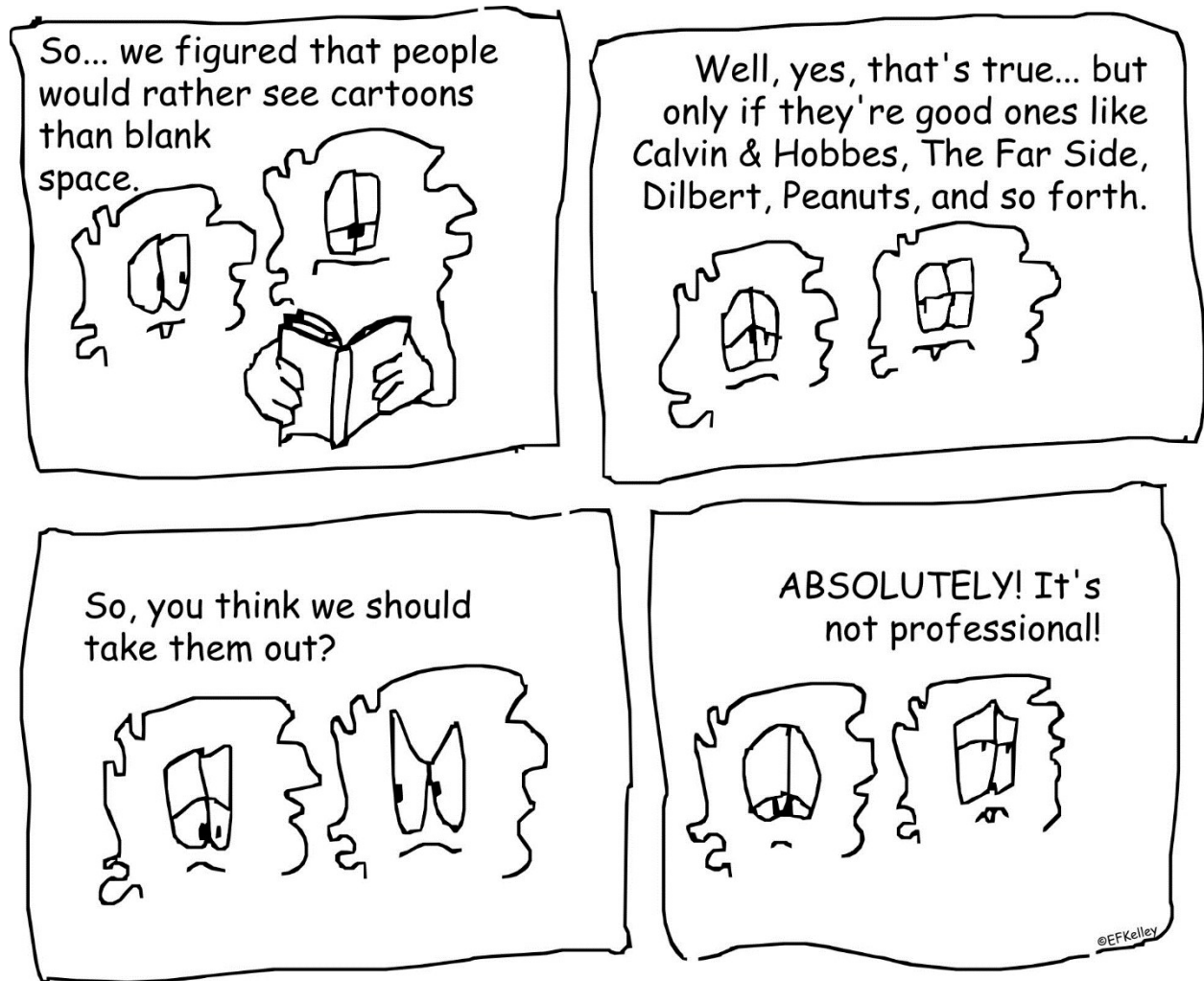


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2. Templates, Composite Metrics, and Suites

This chapter provides a number of reporting templates, suites of measurements, composite metrics, all as suggestions. These are available via the DOI links indicated.



2.1 Display description, identification, and modes

TABLE 2.1 lists the kind of information that is useful to record for keeping a good record of the conditions of the measurements. Some explanation for specifying the colors is in order. The gray scale quantization (“bits per color”) refers to the number of available levels for each primary color, *e.g.*, in an RGB system there may be 5 bits available for red and blue but 6 bits available for green which can be written as “5, 6, 5/RGB”, or “5R, 6G, 5B,” whatever is clear; or if 8 bits are available for each color then we could write “8ea RGB”, or simply “8 each”. The color depth (“total color bits”) refers to the total number of *addressable* colors. Note that this number in most cases is larger than the number of *discernable* colours. In the examples above, the 5, 6, 5/RGB system gives a color depth of 16 bits or 2^{16} addressable levels, and the 8-each system gives 24 bits. Some displays have fixed palettes where the optical output is selected by addressing a look-up table in which the number of entries equals the number of addressable colors. Thus, although a display may be addressable at 8 bits for each primary input RGB giving a palette of 16.78×10^6 colors, if



TABLE 2.1. Typical description and identification information. Gray areas are calculated or default values. A Microsoft® Excel version of TABLE 2.1 is available at DOI: [10.55410/cney4319](https://doi.org/10.55410/cney4319)

DISPLAY INFORMATION				PIXEL DIMENSIONS (optional)		Value	Unit
DUT manufacturer				Nominal ³ resolution			PPI
Model number				Nominal angular resolution			PPD
Serial number				Nominal pitch	Horizontal		μm
Revision level					Vertical		μm
COLORS		Value	Unit	Nominal pixel aspect ratio			
Input primary colors		R, G, B		DETECTOR AND MEASUREMENT		Value	Unit
Gray quantization ¹			bit	Company			
Gray quantization, if not uniform			bit	Model			
Color depth ²			bit	Serial number			
SIGNAL AND POWER		Value	Unit	Measurement distance			mm
Signal source standard				Measurement direction	Azimuth	0	deg
Power source	Voltage		V		Polar	0	deg
	Current		A	Measurement spot location (origin lower left corner)	Horizontal		mm
DISPLAY SIZE AND MECHANICAL FACTS		Value	Unit		Vertical		mm
Active region	Width		mm	Measurement field angle			deg
	Height		mm	Angular aperture			deg
Active area diagonal			in	MEASUREMENT CONDITIONS		Value	Unit
Active area diagonal			mm	Warm-up time used		30	min
Aspect ratio				Room temperature		25	degC
DUT dimensions	Width		mm	Room humidity			%Rh
	Height		mm	Room air pressure			MPa
	Depth		mm	STANDARD SETUP COMPLIANCE (STANDARDS, CLAUSES)			
DUT mass			kg				
Design viewing direction	Azimuth		deg				
	Polar		deg	DEVIATIONS (MUST BE RECORDED)			
Design viewing distance			mm				
DISPLAY DESCRIPTION		Value	Unit				
Input pixel count	Horizontal		px	OTHER INFORMATION			
	Vertical		px	Run or data set number			
DUT technology				Name of test person			
Operational mode (TABLE 2.2)				Date and time tested	2022-08-08, 17:27:30 JST		ISO

Legacy terms: bits per color¹, gray levels¹, total color bits². ³Resolution (spatial response) is to be measured so these items are nominal.

only 256 colors can be displayed at any time, then the total number of colors is 256.

Some displays have different modes of operation whereby modifications are made so that the colors, luminance, contrast, sharpness, dimming or dynamic contrast, gamma, energy savings, etc. are changed for various purposes; we call these *modified-performance modes*. When all these modifications are turned off the display is in its *native-performance* mode. Making measurements in the native-performance mode is often considered a useful mode in which to quantify the performance of the display. In some cases, the goal may be to measure the enhanced-performance modes themselves for analysis or comparison. In that case, the native-performance mode can be used for reference. For reproducibility, it is very important to specify all the settings for all the modes that are measured.

TABLE 2.2 provides a format for reporting the modes that are measured as well as the controls or settings used during the measurement of the display. There can be many controls or settings used by the manufacturer with names such as “contrast”, “brightness”, “color temperature”, “sharpness”, “separate RGB controls”, “tint”, “hue”, “dynamic”,



etc. There is not necessarily a consistency in the display industry among the names of the settings or controls of the display or even what the setting values mean. The name the manufacturer uses for the control or setting is placed in the first column, and the value of that control or setting is placed in the second column. The third column is for describing the control in words that we understand. For example, “Brightness” is usually a luminance level control but may actually be a black level setting in which case we can add a description such as “controls only the black level”. Similarly, “Contrast” may actually be simply a white-level setting and be described by “controls the white level without changing the black level”. Some controls are disabled depending upon the mode of operation; it can be useful to record the disabled controls as well.

TABLE 2.2. Mode of Operation Documentation

Mode Name:		
Control or Setting Name	Control or Setting Value	Control or Setting Description (What the control or setting does.)

2.2 Template For Emissive Displays

This template is available as a Microsoft® Excel file at DOI:[10.55410/SSGD7200](https://doi.org/10.55410/SSGD7200). This file also contains the RGBW chromaticities of reference colour spaces Rec. ITU-R BT.709 (same chromaticities as sRGB), Rec. ITU-R BT.2020 (Rec. 2020), AdobeRGB, DCI-P3, and a custom colour space. Note that emissive displays are displays that emit light, and, in this context, will include LCDs with pixel surfaces that are transmissive using a backlight.

TABLE 2.3. Reporting template for basic measurements of emissive displays. Yellow areas are for measured data and the gray areas calculated values. *Sample data only: Do not use any values shown to represent expected results of your measurements.*

ICDM IDMS			02-Template-EmissiveD_v1.104.xlsx				
DATE:							
Item	Measurement	Section	Input	Value		Unit	Symbol
1a	Full-screen white, luminance	5.3	W	555.7		cd m ⁻²	L _W
1b	Full-screen white, CIE 1931 xy chromaticity	5.3	W	0.315	0.332		x, y
1c	Full-screen white, correlated color temperature	5.3	W	6,432		K	T _C
2a	Color-signal white, luminance	5.4	W	554.7		cd m ⁻²	L _{CSW}
2b	Color-signal white, CIE 1931 xy chromaticity	5.3	W				x, y
2c	Color-signal white, CCT	5.3	W	6,432		K	T _C



3a	Full-screen black, luminance	5.6	K	0.031	cd m ⁻²	L_K
3b	Full-screen black, color	5.6	K	0.3012 0.3124		x, y
3c	Full-screen black, CCT	5.6	K	7,239	K	T_C
4a	Image-signal black, luminance	5.7	K		cd m ⁻²	L_K
4b	Image-signal black, chromaticity	5.7	K			x, y
4c	Image-signal black, correlated color temperature	5.7	K		K	T_C
5a	Full-Screen primary colors, red luminance	5.14	R		cd m ⁻²	L_R
5b	Full-Screen primary colors, red chromaticity	5.14	R	0.64 0.33		x, y
6a	Full-Screen primary colors, green luminance	5.14	G		cd m ⁻²	L_G
6b	Full-Screen primary colors, green chromaticity	5.14	G	0.21 0.71		x, y
7a	Full-Screen primary colors, blue luminance	5.14	B		cd m ⁻²	L_B
7b	Full-Screen primary colors, blue chromaticity	5.14	B	0.15 0.06		x, y
8	Gray scale (col D are the input gray levels, V_i)	6.1	255	555.7	cd m ⁻²	$L(V_9)$
	(using nine levels)		223	415.5	cd m ⁻²	$L(V_8)$
			191	293.6	cd m ⁻²	$L(V_7)$
			159	194.9	cd m ⁻²	$L(V_6)$
			127	115.1	cd m ⁻²	$L(V_5)$
			95	60.83	cd m ⁻²	$L(V_4)$
			63	23.53	cd m ⁻²	$L(V_3)$
			31	4.488	cd m ⁻²	$L(V_2)$
			0	0.031	cd m ⁻²	$L(V_1)$
	Diffuse reflectance of full-screen white	11.2		0.0462		ρ_W
	Diffuse reflectance of full-screen black	11.2		0.0443		ρ_K

Calculations:

9	Sequential luminance contrast	5.10		17,926		C
10	Relative chromaticity area vs. reference colour space. Only calculated for additive displays, $\frac{ L_{CSW}-L_W }{L_{CSW}} < 0.02$.	5.18.1		99%		A_{xy}
11	Gamma from log-log linear regression $L(V_j) = a(V_j - V_K)^\gamma + L_K$	6.3		2.289169657 0.001759837		γ a
12	Design illuminance			500	lx	E_0
	Ambient contrast for design illuminance E_0			80		C_A



2.3 Stereoscopic 3D Displays Template Suite

The following template suite is contained in a Microsoft® Excel® file available at DOI: [10.55410/RQBP2890](https://doi.org/10.55410/RQBP2890). Note that some subscripts and symbols in TABLE 2.4 are different from that of Chapter 17 due to lacking fonts and math-editing support in Excel®; \mathcal{L} , \mathcal{R} , and χ are replaced by L , R , and X , respectively.

TABLE 2.4. Reporting template for basic measurements of stereoscopic 3D displays.
Sample data only: Do not use any values shown to represent expected results of your measurements.

STEREO DISPLAY TESTS (Manual Data Input)			
Display Model:		Light Measuring Device:	
Serial Number:		LMD Set-up:	
Display Width:		Viewing distance:	
Display Height:		Measurement location:	
Date:		Comments:	
Measured by:			

Please note that the cells filled with a yellow color are data-entry cells.

L-R Channel input signal		L	R	Left Eye	CIE 1931 chromaticity		Right Eye	CIE 1931 chromaticity	
(LR)	Fields			L (cd m ⁻²)	x	y	L (cd m ⁻²)	x	y
1	WW	White / White		71.24	0.3067	0.3313	72.60	0.3045	0.3285
2	KW	Black / White		1.986	0.2830	0.2959	70.72	0.3043	0.3285
3	WK	White / Black		67.68	0.3062	0.3307	1.086	0.2762	0.2841
4	KK	Black / Black		0.07776	0.2645	0.2547	0.07820	0.2567	0.2520
5	RK	Red / Black		15.41	0.6152	0.3555	0.2936	0.4926	0.3179
6	GK	Green / Black		47.13	0.3000	0.5902	0.7713	0.2830	0.5150
7	BK	Blue / Black		4.845	0.1450	0.0599	0.1616	0.1633	0.0822
8	KR	Black / Red		0.4813	0.5405	0.3322	16.08	0.6144	0.3553
9	KG	Black / Green		1.389	0.2895	0.5467	49.30	0.2991	0.5895
10	KB	Black / Blue		0.2335	0.1570	0.0727	5.139	0.1451	0.0596

Note: The cells with brown numbers can require very sensitive LMDs to obtain accurate results.

CALCULATIONS:		Left Eye			Right Eye		
Extinction ratio	$C_{\text{sys},L,R}$	35.43	$(L_{LWK} - L_{LKK}) / (L_{LKW} - L_{LKK})$		70.10	$(L_{RKW} - L_{RKK}) / (L_{RWK} - L_{RKK})$	
Crosstalk (%)	$X_{L,R}$	2.823%	$(L_{LKW} - L_{LKK}) / (L_{LWK} - L_{LKK})$		1.390%	$(L_{RWK} - L_{RKK}) / (L_{RKW} - L_{RKK})$	
Monocular contrast	$C_{L,R}$	916.2	L_{LWW} / L_{LKK}		928.4	L_{RWW} / L_{RKK}	
Stereo contrast	C	922.3	$(C_L + C_R) / 2$				
Monocular luminance	$L_{L,R}$	71.24	L_{LWW}		72.60	L_{RWW}	
Binocular luminance	L_{ave}			Arithmetic mean:	71.92	$L_{\text{ave}} = (L_L + L_R) / 2$	
	L_{gmean}			Geometrical mean	71.92	$L_{\text{gmean}} = \text{sqrt}(L_L L_R)$	
Luminance difference	ΔL				1.909%	$(L_L - L_R) / \min(L_L, L_R)$	
					Noticeable > 25%, Loose stereo > 60%		

Calculated CIE 1976 $u'v'$ chromaticity				Left Eye		Right Eye	
L-R Channel input signal		L	R	u'	v'	u'	v'
(LR)	Fields						
1	WW	White / White		0.1928	0.4687	0.1923	0.4668
2	KW	Black / White		0.1891	0.4450	0.1922	0.4668
3	WK	White / Black		0.1927	0.4683	0.1886	0.4366
4	KK	Black / Black		0.1914	0.4147	0.1863	0.4116
5	RK	Red / Black		0.4077	0.5301	0.3380	0.4908
6	GK	Green / Black		0.1266	0.5602	0.1314	0.5381



7	BK	Blue / Black			0.1692	0.1572	0.1785	0.2021
8	KR	Black / Red			0.3661	0.5063	0.4072	0.5299
9	KG	Black / Green			0.1289	0.5478	0.1263	0.5599
10	KB	Black / Blue			0.1765	0.1839	0.1695	0.1566

Note: The cells with brown numbers can require very sensitive LMDs to obtain accurate results.

Calculated Chromaticity Differences

$$\Delta u'v' = \sqrt{(u'_L - u'_R)^2 + (v'_L - v'_R)^2}$$

	L-R deltas	$\Delta u'v'$
White	WK - KW	0.0015
Red	RK - KR	0.0005
Green	GK - KG	0.0004
Blue	BK - KB	0.0007

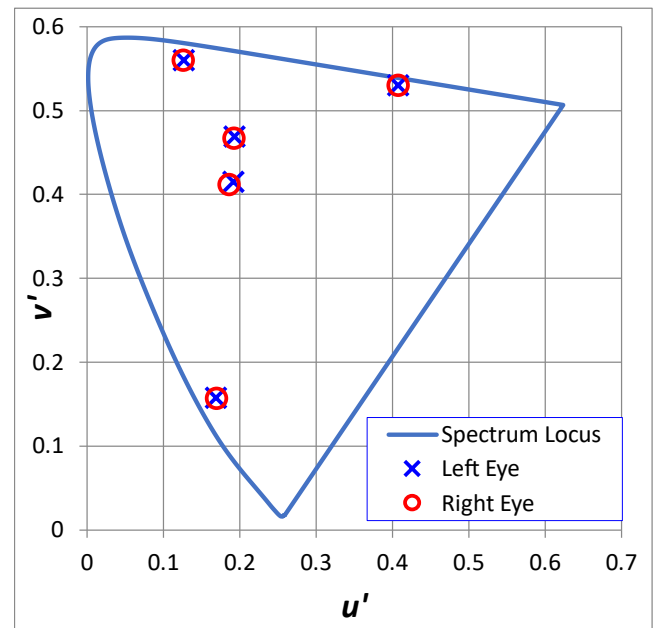
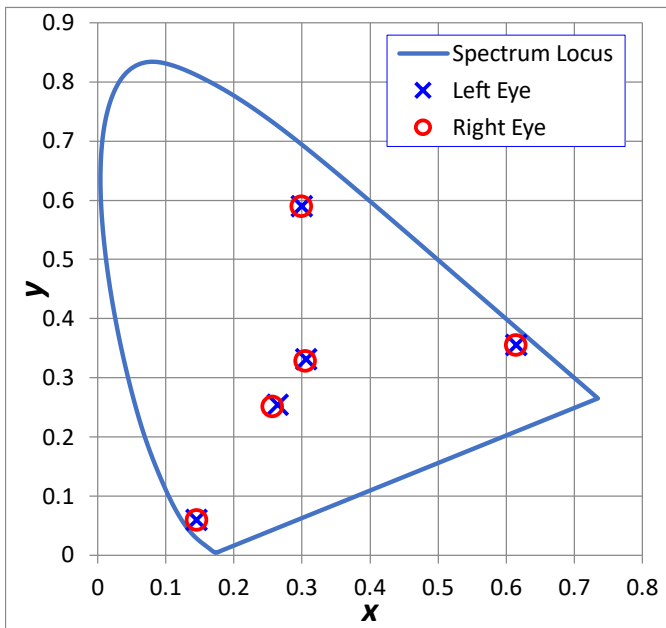
DISPLAYS MEASURED WITHOUT GLASSES

L-R Channel input signal		L	R	Left Eye	CIE 1931 chromaticity		Right Eye	CIE 1931 chromaticity	
Symbol	Fields			L (cd m ⁻²)	x	y	L (cd m ⁻²)	x	y
WW	White / White			72.60	0.3163	0.3157	75.20	0.3136	0.3150
KW	Black / White			29.30	0.2950	0.2981	30.00	0.2934	0.2975
WK	White / Black			29.80	0.2943	0.2976	30.70	0.2932	0.2977
KK	Black / Black			0.07600	0.2557	0.2499	0.07700	0.2559	0.2478

Note: The cells with brown numbers can require very sensitive LMDs to obtain accurate results.

CALCULATION OF GLASSES TRANSMISSION

%T			
Left	Right	Sum	
30.60%	33.00%	63.60%	
0.2000%	26.60%	26.80%	Average:
25.10%	0.300%	25.40%	24.40%
43.30%	36.10%	79.40%	

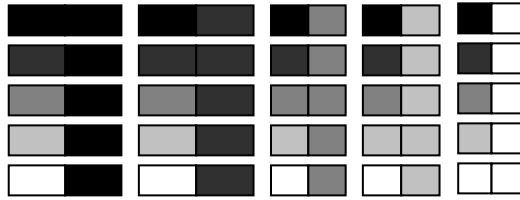




Chapter 2 – Templates, Composite Metrics, and Suites

3D GRAY TO GRAY CROSSTALK

For $n=5$ levels



Luminance values

		Left eye (L_{Lij})					Right eye (L_{Rij})				
j	i	1	2	3	4	5	1	2	3	4	5
	V_{ij}	0	63	127	191	255	0	63	127	191	255
1	0	0.07776	0.1783	0.5331	1.116	1.986	0.07820	3.785	17.09	38.41	70.72
2	63	3.796	4.102	4.613	5.295	6.268	0.1299	3.967	17.47	38.91	71.08
3	127	16.57	17.21	17.89	18.68	19.76	0.3130	4.223	17.81	39.32	71.48
4	191	36.85	37.70	38.52	39.42	40.65	0.6149	4.577	18.23	39.83	72.00
5	255	67.68	68.15	68.98	69.96	71.24	1.086	5.082	18.76	40.45	72.60
		Crosstalk numerator ($L_{Lij} - L_{Lji}$)					Crosstalk numerator ($L_{Rij} - L_{Rji}$)				
1	0		0.10054	0.455	1.038	1.908		-0.1820	-0.7200	-1.420	-1.880
2	63	-0.306		0.511	1.193	2.166	0.0517		-0.3400	-0.9200	-1.520
3	127	-1.320	-0.680		0.790	1.870	0.2348	0.2560		-0.5100	-1.120
4	191	-2.570	-1.720	-0.900		1.230	0.5367	0.6100	0.4200		-0.6000
5	255	-3.560	-3.090	-2.260	-1.280		1.008	1.1150	0.9500	0.6200	
		Crosstalk denominator ($L_{Lji} - L_{Lij}$)					Crosstalk denominator ($L_{Rji} - L_{Rij}$)				
1	0		3.718	16.49	36.77	67.60		-3.837	-17.50	-39.22	-71.51
2	63	-3.924		13.11	33.60	64.05	3.707		-13.59	-35.25	-67.52
3	127	-17.36	-13.28		20.63	51.09	17.01	13.50		-21.60	-53.84
4	191	-38.30	-34.13	-20.74		30.54	38.33	34.94	21.51		-32.15
5	255	-69.25	-64.97	-51.48	-30.59		70.64	67.11	53.67	32.17	
		Crosstalk					Crosstalk				
		$X_{Lij} = 100 \text{ abs}[(L_{Lij} - L_{Lji}) / (L_{Lji} - L_{Lij})]$					$X_{Rij} = 100 \text{ abs}[(L_{Rij} - L_{Rji}) / (L_{Rji} - L_{Rij})]$				
1	0		2.704	2.761	2.823	2.823		4.743	4.115	3.621	2.629
2	63	7.799		3.898	3.551	3.382	1.395		2.502	2.610	2.251
3	127	7.605	5.122		3.829	3.660	1.380	1.896		2.361	2.080
4	191	6.709	5.040	4.339		4.028	1.400	1.746	1.953		1.866
5	255	5.140	4.756	4.390	4.184		1.427	1.661	1.770	1.927	
		Left eye					Right eye				
Average:		$X_{Lave} =$	4.427				Average:	$X_{Rave} =$	2.267		
Stdev:		$S_{XLave} =$	1.493				Stdev:	$S_{XRave} =$	0.921		
Max:		$X_{Lmax} =$	7.799				Max:	$X_{Rmax} =$	4.743		



2.4 Vantage-Point Suite of Measurements

The following suite is contained in a Microsoft® Excel file that is available at DOI: [10.55410/UJKF9035](https://doi.org/10.55410/UJKF9035).

DESCRIPTION

Measure the viewing angle characteristics of a display the way it is observed by a user: by fixing the observer's position in front of the display center, then view various parts of the screen from that fixed vantage point. The display is viewed from a fixed vantage point, and for this measurement, the display is measured in the same way.

These basic tests make a number of measurements at five positions on the screen. Then calculations are applied to compare them and produce a suite of metrics which describe the display's viewing direction performance from the user's point of view, or vantage point. This suite of measurements strives to keep the viewer's perspective in mind.

APPLICATION

These measurements can be used for any display but are primarily intended for displays which have viewing angle dependencies, such as LCDs. It is optimal for monitors, notebook displays, or other displays which are viewed by a single user at a fixed position near the center of the screen. However, it can also be a good test for viewing direction performance for other applications even when they are not viewed in the same manner as these measurements.

These measurements can also be used for projection screens, where the measurement distance is adjusted to be the approximate distance of the viewer closest to the screen. Note that the measurements will not be done normal to the screen. Rather, the center of the screen will be viewed ideally from the horizontal center but offset for the vertical direction to avoid blocking of the projector light (tilted LMD).

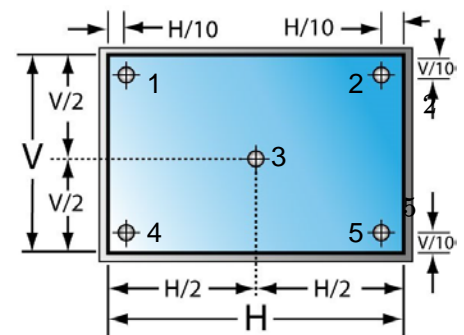


FIGURE 2.1. Measurement locations using 5 positions

SETUP



As defined by these icons, standard setup details apply (section 3.2).

SETUP CONDITIONS FOR CENTER REFERENCE MEASUREMENT

A luminance and colorimetric spot-photometer type light measuring device (LMD) is used to measure the important characteristics of the display.

- The display is in a fixed position for the entire test.
- The LMD should be mounted on a tripod or other device which allows for pivoting about its entrance pupil in the vertical and horizontal directions in order to make measurements at various points on the display.
- We typically measure five points, where the center point is number 3 and the corner points are 1, 2, 4, and 5, from upper left to bottom right (see FIGURE 2.1).
- Measurement distance: Viewing distance from the center of the screen, then variable distances to the corners and other points on the screen. Optimum viewing distance is determined by the application and/or by the required angular resolution in terms of cycles (line pairs) per degree (CPD) in the observer's field of view. The maximum angular resolution of the human visual system (HVS) is 60 CPD.
- Measurement field angle (aperture): 1° typical.



SETUP CONDITIONS FOR OFF-ANGLE MEASUREMENT POINTS



PROCEDURE

1. Set up the LMD to measure the center of the display, perpendicular (normal) to it. This is the reference measurement point. Measurements of other points on the display will use the center as the reference to determine their metrics. That is, the calculations for comparison will be based on the measured parameters at the center of the screen.
2. Measure all the parameters of the Vantage-Point Suite for the center of the screen and report them. The same measurements will be used for all of the points to be measured. Only the viewing direction will change from point to point. Use the positioning points per FIGURE 2.1 to determine where to measure. Assure that the measurement aperture does not extend beyond the edge of the display.
 - a. Full screen white - Luminance, chromaticity coordinates, CCT
 - b. Full screen black - Luminance
 - c. Full screen red - Luminance, chromaticity coordinates
 - d. Full screen green - Luminance, chromaticity coordinates
 - e. Full screen blue - Luminance, chromaticity coordinates
 - f. Optional measurements for all points
 - i. Gamma
 - ii. Red, Green, and Blue gammas for color tracking
 - iii. Response Time
 - iv. Ambient illumination measurements
 - v. Gray scale inversion
 - vi. Color inversion
3. Adjust the LMD to the next point to be measured, tilt the LMD at its central pivot point. Adjust the viewing direction to the point so that the outer edges of the area covered by the aperture of the LMD does not extend over the edges of the active area. Readjust the focus as needed.
4. Measure all the parameters of the Vantage Point Suite relative to the center point and aim the LMD to each successive point of the measurement suite until all points are measured.
5. Report the measured results per TABLE 2.5.



TABLE 2.5. Data reporting example of vantage point measurements. The gray areas are automatically calculated.
Sample data only: Do not use any values shown to represent expected results of your measurements.

Point	Position*	White				Black	C	Red			Green			Blue		
		L_W	u'_W	v'_W	T_C	L_R		L_R	u'_R	v'_R	L_R	u'_G	v'_G	L_R	u'_B	v'_B
1	UL	100.8	0.2043	0.486	5287	0.421	239.4	25.65	0.3889	0.5289	68.55	0.1289	0.5621	8.55	0.154	0.21
2	UR	109.8	0.1936	0.5007	5308	0.3803	288.7	27.47	0.4107	0.5324	75.02	0.1214	0.5663	9.04	0.1462	0.2323
3	Center	243.4	0.1958	0.4844	5806	0.37	657.8	58.22	0.4243	0.5323	164.4	0.1259	0.563	20.72	0.1519	0.2028
4	LL	111.9	0.1932	0.4998	5352	0.392	285.5	28.49	0.4086	0.5322	75.98	0.1203	0.5658	9.39	0.1463	0.2327
5	LR	103.8	0.2033	0.487	5318	0.403	257.6	25.99	0.4304	0.529	71.2	0.1291	0.5625	8.66	0.1551	0.2082
Maximum		243.4	0.2043	0.5007	5806	0.421	657.8	58.22	0.4304	0.5324	164.4	0.1291	0.5663	20.72	0.1551	0.2327
Minimum		100.8	0.1932	0.4844	5287	0.37	239.4	25.65	0.3889	0.5289	68.55	0.1203	0.5621	8.55	0.1462	0.2028

*Measurement positions: UL=upper left; UR=upper right; LL=lower left; LR=lower right. Center is normal to the screen and used as the reference for all other off-angle measurements.
 For calculation of the correlated color temperature T_C , see section B1.2.1. Luminance ratio is the calculated value $C = L_W L_K^{-1}$.

ANALYSIS

A variety of performance metrics can be determined from the measurement data summarized in TABLE 2.5. The white point can be represented by the correlated color temperature (CCT), T_C , following the method in B1.2.1.

The sampled luminance and contrast ratio nonuniformity are often expressed in terms of the minimum and maximum values measured over the image, and have the following form:

$$N = 100\% \frac{\xi_{\max} - \xi_{\min}}{\xi_{\max}} \quad (2.1)$$

where ξ is any of the symbols in TABLE 2.5.

The chromaticity difference $\Delta u'v'$ between any two colors can be expressed as the Euclidean distance between their chromaticity coordinates in the CIE 1976 chromaticity diagram using the following expression:

$$(\Delta u'v')_{ij} = \sqrt{(u'_i - u'_j)^2 + (v'_i - v'_j)^2} \quad (2.2)$$

where i and j represent the i th and j th colors, with $i \neq j$, in a series of chromaticity measurements. The chromaticity nonuniformity over an image from a single color can be expressed as the largest chromaticity difference $\Delta u'v'$ between any two measured chromaticities in the image.

A simple metric for representing the color range is the chromaticity gamut area, which is applicable if the DUT exhibits color additivity. It is determined by measuring the CIE 1931 xy chromaticity coordinates of the RGB primaries at maximum input signal level. The gamut area A_{xy} enclosed by the RGB primary triangle in the CIE 1931 xy chromaticity diagram relative to the area of the entire spectrum locus is determined by the following equation:

$$A_{xy} = 149.6 |(x_R - x_B)(y_G - y_B) - (x_G - x_B)(y_R - y_B)| \quad (2.3)$$

where the subscripts R, G, and B refer to the red, green, and blue primaries, respectively. See section 5.18 for a full description of the chromaticity gamut area.



CAUTION: The chromaticity gamut area presumes that the DUT exhibits luminance additivity (see 5.4). If the DUT does not exhibit luminance additivity, the method in 5.32 shall be used for evaluating the color range of the DUT.

SUPPLEMENTAL INFORMATION

Report the measurement angles using display active area dimensions in width (cm) and height (cm). For simplicity, enter the pixel array $N_H \times N_V$ and the diagonal D in inches. Then,

$$N_T = N_H \times N_V \quad (2.4)$$

$$D_{\text{cm}} = D \times 2.54 \quad (2.5)$$

$$H = \sqrt{\frac{D_{\text{cm}}^2 \times N_H^2}{N_H^2 + N_V^2}} \quad (2.6)$$

$$V = \sqrt{D_{\text{cm}}^2 - H^2} \quad (2.7)$$

where N_T is the total number of pixels, D_{cm} the diagonal size in cm, H the horizontal size in cm, V the vertical size in cm.

If the measurement distance to the center of the display is d_v and Δ the inclination of a titled display around the vertical axis ($\Delta = 0$ for a display aligned perpendicularly to the LMD), then the LMD pivot angles become:

$$\theta_{\text{top,corner}} = \tan^{-1} \frac{\sqrt{\left(\frac{H}{2} + \Delta\right)^2 + \left(\frac{V}{2}\right)^2}}{d_v} \quad (2.8)$$

$$\theta_{\text{mid}} = 0 \quad (2.9)$$

$$\theta_{\text{bottom,corner}} = -\tan^{-1} \frac{\sqrt{\left(\frac{H}{2} + \Delta\right)^2 + \left(\frac{V}{2}\right)^2}}{d_v} \quad (2.10)$$

and the azimuthal angles

$$\varphi_{\text{left}} = -\tan^{-1} \frac{0.5H + \Delta}{d_v} \quad (2.11)$$

$$\varphi_{\text{center}} = 0 \quad (2.12)$$

$$\varphi_{\text{right}} = \tan^{-1} \frac{0.5H + \Delta}{d_v} \quad (2.13)$$

A reporting example of this supplemental information is shown in TABLE 2.7

REPORTING

From the measured results calculate the performance per TABLE 2.5. A reporting example is shown in TABLE 2.6.



COMMENTS

- 2.1 *Number of points:* This test suite can be done for 5 points, 9 points (3×3), or 25 points (5 rows of 5 points evenly distributed), per the interested party's choice. Measurements at the corners and edges give the greatest angular deviation from the reference point at the center of the screen, so there is no need to measure more than 25 points.
- 2.2 *Measurement distance:* If the desired measurement distance is not achievable for an LMD due to minimum focus distance, then increase the distance until the LMD is in proper focus at the center of the screen. Try to get as close to the desired distance as possible.
- 2.3 *LMD mount geometrical center:* The typical mounting mechanism for the LMD (such as a tripod) and the LMD attachment position to the mount almost certainly assures that the pivoting of the LMD will not be geometrically centered. That is to say that the pivot point may be non-symmetrical with the pivot of the LMD entrance pupil, and the measurement distance from the entrance pupil to the topmost points and bottom points is unlikely to be the same. Although this is not desirable, this test accounts for such test set alignment issues by taking the worst case of the points for measurement calculations. However, when reporting the measurement distance to each point as well as the viewing direction (in terms of θ and φ), care should be given to account for the non-symmetrical angles and distances.
- 2.4 Typically in display viewing direction measurements, the LMD is fixed to measure only the center of the display and the display pivots about the center to the various viewing directions to be measured. Many measurements with that method result in a viewing cone emanating from the center. In this test method, the display remains fixed, and the LMD changes direction to look about the extremities of the display. For these measurements, the measurement distance changes for each point measured. This may be visualized as an inverse of the viewing cone, where the center of the cone is where the display would be viewed by eye and the cone spreads as it nears the display screen.

TABLE 2.6. Data reporting example of vantage point measurements.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Parameter	Input signal	Value	Specification	Values	Pass/fail
Measurement distance to screen center	N/A	300 mm	300 mm	Values	Pass/fail
Measurement aperture field of view	N/A	1°	1°		
Chromaticity nonuniformity ($\Delta u'v'$) _{max}	W	0.01636		($\Delta u'v'$) _{max}	
	R	0.01570			
	G	0.00623			
	B	0.03043			
Luminance nonuniformity (%)	W	51.3		Maximum	
	R	55.3			
	G	50.2			
	B	79.5			
	K	12.1			
Luminance ratio nonuniformity (%)	W/K	63.6		Maximum	
CIE 1931 xy chromaticity gamut area A_{xy}	Calculation	65.0538		Minimum	
	Calculation	97.6		Minimum	
Center luminance ratio	$C = L_W L_K^{-1}$	265.0539		Minimum	
CCT nonuniformity (%)	W	8.9390		Maximum	
Non-monotonic electro-optic transfer function	N/A	Yes/No	None Allowed	N/A	
	N/A	Yes/No	None Allowed	N/A	



TABLE 2.7. Supplemental data reporting example of vantage point measurements. The gray areas are automatically calculated.
Sample data only: Do not use any values shown to represent expected results of your measurements.

Parameter	Symbol	Unit	Value				
Horizontal signal pixels	N_{H}	px	1280				
Vertical signal pixels	N_{V}	px	1024				
Diagonal size in inches	D	inch	17.0				
Width of active area	H	mm	337.18				
Height of active area	V	mm	269.74				
Display vertical rotation	Δ_{θ}	°	0.00				
Display horizontal rotation	Δ_{φ}	°	0.00				
Diagonal size	D_{mm}	mm	431.80				
Aspect ratio			1.25				
Measurement location			Point 1 (UL)	Point 2 (UR)	Point 3 (Ctr)	Point 4 (LL)	Point 5 (LR)
LMD elevation (tilt)	θ	°			0.00		
LMD azimuth (pan)	φ	°			0.00		
Distance to measured points	d_{v}	mm					

Note: The default display rotation and LMD tilt/pan is 0°. Other values are obtained from the Vernier scales of the fixtures.

2.5 Luminance and Chromaticity Uniformity Template

See FIGURE 2.1 of section 2.4 for location numbering of the 5-point case. The tables are contained in a Microsoft® Excel file that is available at DOI: [10.55410/PBMV7989](https://doi.org/10.55410/PBMV7989)

TABLE 2.8. Reporting sheet for dark-room uniformity measurements of white luminance, luminance ratio, chromaticity, and CCT.
The gray areas are calculated automatically. Point 5 is the center point for uniformity reference.

Number of locations		White					Black	Luminance ratio
9 pt.	5 pt.	L_W (cd m ⁻²) (Section 5.3)	CIE 1931 x (Section 5.14)	CIE 1931 y (Section 5.14)	T_C (K) (Section B1.2.1)	$\Delta u'v'$ (Section 2.4)	L_K (cd m ⁻²) (Section 5.6)	C (Section 5.9)
1	1							
2								
3	2							
4								
5	3							
6								
7	4							
8								
9	5							
Average								
Minimum								
Maximum								
Nonuniformity, (8.1)								
See Eq. (2.1) for the definition of nonuniformity					$C = L_W L_K^{-1}$			

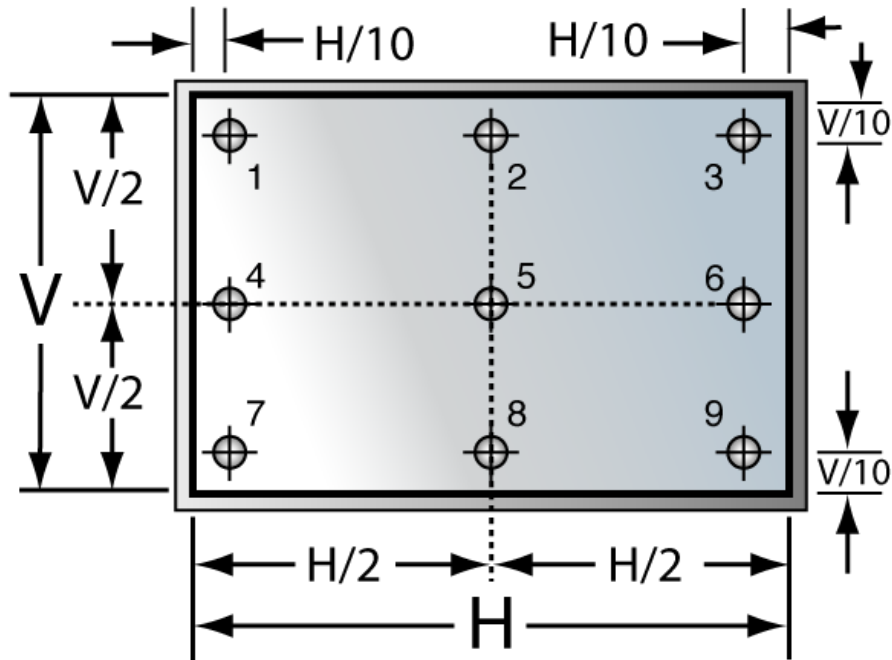


TABLE 2.9. Luminance and contrast ratio uniformity reporting sheet for darkroom measurements. The gray areas are automatically calculated. *Sample data only: Do not use any values shown to represent expected results of your measurements.*

Test pattern: Full screen		LMD: LMD1, 2° aperture					
Measurement position		White	Red	Green	Blue	Black	Luminance ratio
9 pt.	5 pt.	L_W (cd m ⁻²)	L_R (cd m ⁻²)	L_G (cd m ⁻²)	L_B (cd m ⁻²)	L_K (cd m ⁻²)	$L_W L_K^{-1}$ (cd m ⁻²)
1	1	100.8	25.65	68.55	8.55	0.421	239.5
2							
3	2	109.8	27.47	75.02	9.04	0.3803	288.72
4							
5	3	243.4	58.22	164.4	20.72	0.37	657.84
6							
7	4	111.9	28.49	75.98	9.39	0.392	285.5
8							
9	5	103.8	25.99	71.2	8.66	0.403	257.56
Average		133.94	33.164	91.03	11.272	0.39326	345.824
Minimum		100.8	25.65	68.55	8.55	0.37	239.5
Maximum		243.4	58.22	164.4	20.72	0.421	657.84
Nonuniformity (8.1)		58.6%	55.9%	58.3%	58.7%	12.1%	63.6%



TABLE 2.10. Chromaticity reporting sheet for darkroom measurements
Sample data only: Do not use any values shown to represent expected results of your measurements.

Device description: DUT1											
Test pattern: Full screen						Alignment method: Perpendicular					
Measurement position		White		Red		Green		Blue		Black	
9 pt.	5 pt.	u'	v'	u'	v'	u'	v'	u'	v'	u'	v'
1	1	0.2043	0.486	0.3889	0.5289	0.1289	0.5621	0.154	0.2100	0.2043	0.486
2											
3	3	0.1936	0.5007	0.4107	0.5324	0.1214	0.5663	0.1462	0.2323	0.1936	0.5007
4											
5	5	0.1958	0.4844	0.4243	0.5323	0.1259	0.5630	0.1519	0.2028	0.1958	0.4844
6											
7	7	0.1932	0.4998	0.4086	0.5322	0.1203	0.5658	0.1463	0.2327	0.1932	0.4998
8											
9	9	0.2033	0.4870	0.4304	0.5290	0.1291	0.5625	0.1551	0.2082	0.2033	0.4870

TABLE 2.11. Example of a chromaticity nonuniformity reporting sheet for dark room measurements. The gray area is automatically calculated. *Sample data only: Do not use any values shown to represent expected results of your measurements.*

Device description: DUT1												
Test pattern: Full screen						Alignment method: Perpendicular						
Measurement position		White $\Delta u'v'$										
9 pt.	5 pt.	u'_i	v'_i	1	2	3	4	5	6	7	8	9
1	1	0.2043	0.4860									
2												
3	3	0.1936	0.5007	0.0182								
4												
5	5	0.1958	0.4844	0.0086		0.0164						
6												
7	7	0.1932	0.4998	0.0010		0.0010		0.0156				
8												
9	9	0.2033	0.4870	0.0168		0.0168		0.0079		0.0163		
Result: $(\Delta u'v')_{\max} = 0.0182$												

2.6 Center Screen Basic Measurements Template

DESCRIPTION

Measure the center luminance, chromaticity, white CCT, white/black luminance ratio, and chromaticity gamut area of the for the primary colors (RGB). Units: various; and Symbol: various.

Absolute center photometric and colorimetric measurements are performed using a full screen pattern. Other patterns may also be used as necessary. Unless stated otherwise, the luminance of white and the primary colors will be measured by supplying the display with the maximum signal for the R, G and B input channels.

ADDITIONAL SETUP

The same setup conditions are used as the main section.



PROCEDURE

Same as main section.

ANALYSIS

Same as main section.

REPORTING

Report values of all measured colors. See example template in TABLE 2.12.

TABLE 2.12. Center of virtual image basic measurements reporting sheet for dark room measurements. The gray areas are calculated automatically. This table is available as a Microsoft® Excel® file at DOI: [10.55410/FMTU4763](https://doi.org/10.55410/FMTU4763).

Sample data only: Do not use any values shown to represent expected results of your measurements.

Input signal	L (cd m ⁻²)	CIE 1931 x	CIE 1931 y	T_C (K)	Contrast $L_W L_K^{-1}$	Chromaticity area gamut (%)
	Section (5.3)	Section (5.14)	Section (5.14)	Section (B1.2.1)	Section (5.9)	Section (5.18)
White	243.40	0.3373	0.3567	5805	657.8	31.6
Red	58.22	0.6334	0.3532	N/A		
Green	164.40	0.3024	0.6009			
Blue	20.72	0.1414	0.0839			
Black	0.37	0.3373	0.3567	5805		

2.7 Color-Tile Characterization

Measure all nine boxes for all five patterns (either from the normal or from the design viewing location or vantage point). Those measurement results will provide the average luminance, average chromaticities, overall contrast, and uniformity of RGBWK. It will be important to use a frustum or stray-light elimination tube (SLET, see A2.1.1 and A2.1.5) particularly for black.



FIGURE 2.2. Test patterns for color-tile characterization.



3. Setup of Display and Apparatus

The yellow arrow and small coordinate lines in FIGURE 3.1 indicate where the detector is pointing and the surface upon which it is focused (assuming it has a lens) or the approximate region from which light is being measured. The blue arrows in FIGURE 3.2 show the configuration of the apparatus relative to the coordinate system, which is detailed in section 3.5. We often show equipment diagrams with fictitious equipment. No attempt is made to represent any manufacturer, and any resemblance is accidental. We often show such equipment with the lights on and with a white background so the configuration example can be seen. In actuality, darkroom conditions should be used in most cases (if we rendered the images under simulated darkroom conditions the equipment wouldn't be very visible).

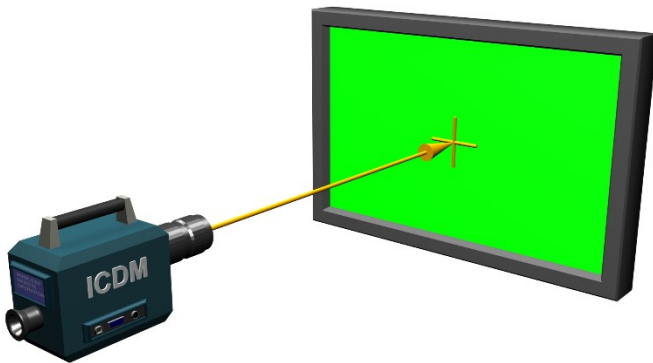


FIGURE 3.1. Arrow showing pointing direction and focal point of the detector (cross).

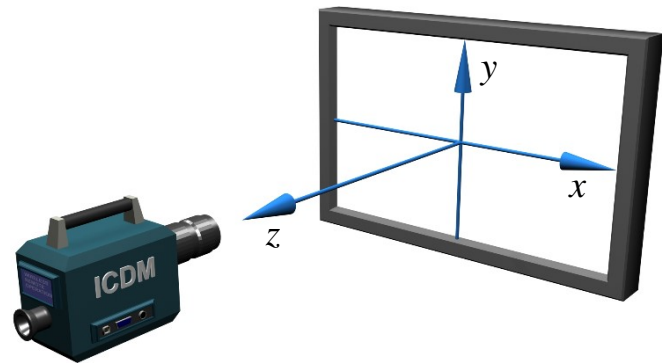


FIGURE 3.2. Arrows showing Cartesian coordinates (x, y, z) centered on the display screen.

3.1 Apparatus for Measurements

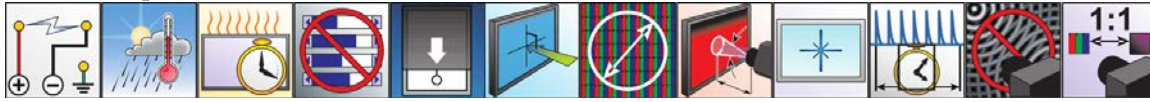
A variety of instruments can be employed in making measurements of light. We often refer to such an instrument as a light-measurement device (LMD), but “detector” is also used in this document interchangeably or together with LMD. The Metrology Appendix A1 Light-Measurement Devices discusses the various types of instruments and their requirements in detail. Here is a summary of their requirements:

1. **Luminance Measurements:** For CIE Illuminant A: The relative uncertainty with coverage factor of two must be $U_{\text{LMD}} \leq 4\%$ with repeatability $\sigma_{\text{LMD}} \leq 0.4\%$ over 5 min, and the deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f'_1 \leq 8\%$.
2. **Illuminance Measurements:** For CIE Illuminant A: The relative uncertainty with coverage factor of two must be $U_{\text{LMD}} \leq 4\%$ with repeatability $\sigma_{\text{LMD}} \leq 0.4\%$ over 5 min, the deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f'_1 \leq 8\%$, and the directional response error must be $f_2 \leq 2\%$.
3. **Chromaticity Measurements:** For CIE Illuminant A: For all instruments measuring chromaticity, the expanded uncertainty U_{col} with a coverage factor of two in measurement of CIE 1931 (x, y) chromaticity coordinates must be $U_{\text{col}} \leq 0.005$ with repeatability $\sigma_{\text{col}} \leq 0.002$.
4. **Radiance Measurements:** For a spectroradiometer with a 380 nm to 780 nm coverage, the relative expanded uncertainties with coverage factors of two must be $\leq 2\%$ for the 400 nm to 700 nm range and $\leq 5\%$ for the 380 nm to 400 nm range and the 700 nm to 780 nm range.
5. **Array Detector Measurements:** For luminance measurements on a CIE Illuminant A uniform source: Relative uncertainty with coverage factor of two $U_{\text{LMD}} \leq 4\%$ with repeatability $\sigma_{\text{LMD}} \leq 0.4\%$ over 5 min, the deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f'_1 \leq 8\%$, and any 10×10 detector-pixel measurement region average must be within 2% of the entire array average at a $50\% \pm 10\%$ saturation.



3.2 Standard Conditions (Setup Icons)

Those familiar with display measurement techniques generally do not need to be reminded of what setup conditions need to be met. In most measurement descriptions we relegate these repeated requirements to icons that are defined in this section. The most common grouping of them generally appears in the following form. With the use of array cameras, the two icons at the far right may appear from time to time. We provide a summary in TABLE 3.1 and fuller descriptions in subsections below.



Any deviations from these setup conditions must be noted in any reporting documentation.

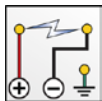
TABLE 3.1. Standard (default) setup conditions as represented by setup icons—a summary.

Deviations and exceptions from these setup conditions must be documented and reported to all interested parties.

For LMD nomenclature see section 3.7 Variables and Nomenclature.

	Electrical conditions are identified, documented, and properly met.		500 px is the default number of pixels to be measured (diameter of approximately 26 px).
	Environmental conditions: 24 ± 5 °C, 84 – 106 kPa (25 – 31 mm Hg) 25 – 85% Rh (non-condensing)		Measurement field angle of 2° or less (infinite focus). Angular aperture of acceptance area (often the subtense of the lens or detector area) no greater than 2°. Exceptions must be verified. Reasonable distance maintained.
	Warm-up time: 20 min minimum nominally (we prefer a sufficient time to establish stability of the luminance of a full white screen to less than 1% drift per hour).		Center screen measurement (or otherwise specified) with placement uncertainty of 3% of the screen diagonal.
	Controls must remain unchanged during all measurements, and the display mode of operation must be specified if there is more than one mode.		Adequate integration time of detection for repeatable measurement.
	Darkroom conditions: 0.01 lx or less with no obvious sources of light visible from the viewpoint of the display, <i>e.g.</i> , equipment lights and computer display reflections off the walls.		Avoid moiré and aliasing when using an array detector.
	Perpendicular viewing direction (or otherwise specified for the intended use) with uncertainty goal of 0.3°.		Configure an array detector so there is a one-to-one mapping between the display pixel and the detector pixel.

3.2.1 Electrical Conditions



The electrical conditions must be identified, documented (on the display or in its manual is adequate documentation), and properly met if specified by the manufacturer. Otherwise, deviations must be reported to all interested parties. If it is a battery operated device, an AC adapter is preferred so that the measurement results do not depend upon the battery condition.



3.2.2 Environment



The following environmental conditions must be obtained: $24 \pm 5^\circ\text{C}$, 84 – 106 kPa (25 – 31) mm Hg. These are the air pressures for approximately 1609 m (5280 ft or 1 mile) down to a little below sea level, for sea level (101.325 kPa, 29.92 mm Hg). 25 – 85% Rh (non-condensing). Should any of these conditions not be met, then they must be reported to all interested parties.

3.2.3 Warm-Up Time



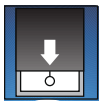
The display must be warmed up for a minimum of 20 min. Longer warm-up times are encouraged to the point that the display exhibits less than a 1% drift per hour. Special situations arise where either a longer or shorter warm-up is required. In such a case, deviations must be reported to all interested parties.

3.2.4 Controls Unchanged and Modes



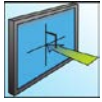
The mode of operation and the controls or settings that can adjust the performance of the displays must be recorded and remain unchanged during all measurements. Once they are adjusted properly, they must remain unchanged for all measurements. Some special displays are adjusted for certain types of tasks where the controls must be changed. In such a case, any control changes must be *clearly* reported to all interested parties.

3.2.5 Darkroom Conditions



For general measurements in the dark, the illuminance in the plane of the display must be 0.01 lx or less. In addition, there should be no obvious sources of light (equipment lights, reflection of computer screens off walls or people) that are visible from the viewpoint of the display being measured. See the Reflection Chapter (12) for measurements under carefully controlled ambient illumination.

3.2.6 Standard Viewing Direction



Measurements shall be made from the perpendicular direction the normal being determined at the center of the screen as shown; this is the standard viewing condition. There are some cases where we want to know the display characteristics in a certain viewing direction in front of the display, design viewing direction, and so forth. Such non-perpendicular viewing conditions must be noted and communicated to all interested parties. For projection display measurements this icon is meant to require that the illuminance meter is held with its axis perpendicular to the screen; it would not be pointed at the projector no matter where it is on the projection screen. Please see A15 Establishment of Perpendicular in the Metrology Appendix for details of several methods commonly employed.

3.2.7 Number of Pixels Measured



Unless specified otherwise in a particular measurement method, measure an area of at least 500 px, which is a circular area with a 26 px diameter. This way, small deviations from average exhibited by a few pixels will not seriously change the measurement result. The use of instruments that measure fewer than 500 px is acceptable provided they can be verified to produce the same results as instruments that do measure at least 500 px.

3.2.8 Measurement Field, Angular Aperture, and Distance



The typical standard measurement distance in this document is 500 mm and is based upon the use of computer monitors. Assure that both the measurement-field angle at infinity and the angular aperture at 500 mm are 2° or less for any luminance (radiance) or color measurement. Some LMDs cannot focus closer than 1 m and other instruments must be used at a distance of only a few millimeters as with conoscopic LMDs; such LMDs can be used provided that their results will agree with LMDs used at the standard measurement distance of 500 mm. Many hand-held displays should be measured at a distance of 250 — 400



mm. Many television displays will be measured at greater distances as will front-projection displays. Thus, there can be no set distance required for all displays. *NOTE: If 500 mm is not used then the distance used must be reported and agreed upon by all interested parties. In all cases the distance must be appropriate for the LMD that is used.*

The suggested method of choosing a proper measurement distance that is independent of the type of display is based on a limit of the average human visual acuity, which is 48 pixels/degree[3.1] of visual angle (others have used 60 px/degree[3.2] for excellent vision of bright targets). For more information, see the appendix A4.1 Number of Measured Pixels. To convert this resolution limit to a distance, $D = 48P \div \tan 1^\circ = 2750P$, where P is the pixel size assuming square pixels. (For 60 px/degree, $D = 60P \div \tan 1^\circ = 3437P$) As an example, a full HD display has a pixel count of 1920×1080 pixels. Applying the 2750 pixel distance would indicate a measurement distance that is 2.54 times the screen height V , $D = 2750 \div 1080V$, which is a typical working distance for a television (60 px/degree will give approximately 3.18 screen heights).

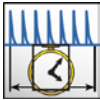
For entertainment television the 2750 P distance is optimal for viewing. Then you will be readily seeing all the pixels you are paying for. For computer monitors a 500 mm distance will often be less than the 2750 P distance because you may normally want to see better than the pixel resolution for ease of reading fine text.

3.2.9 Screen Measurement Points



Unless specified otherwise in a particular measurement method, the standard measurement point on the screen will be the center of the screen. Uniformity measurements will violate this condition by definition. Any other deviation must be reported to all interested parties.

3.2.10 Integration Time Sufficient



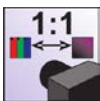
Bright displays can introduce detector integrations problems dramatically increasing measurement uncertainty. Be sure that your measurement results of bright displays are not affected by too short of an integration time; too short an integration time will manifest itself by a large repeatability uncertainty. See the appendix A4 Measurement Time Interval for more information.

3.2.11 Array Detector Alias Avoidance



Be smart when you use an array detector. **(1)For large area measurements:** The closer you get to the case where one detector pixel is measuring approximately one display pixel or display subpixel, the more problems you will have with aliasing and moiré. Sometimes defocusing or using a diffusion lens (from a photography store) can help. **(2)For the examination of pixel detail:** The more detector pixels that are employed per display pixel, the safer you will generally be. Try for 10 or more detector pixels for a display subpixel or 30 or more detector pixels per display pixel.

3.2.12 Array Detector Pixel 1:1 Correspondence



Under certain conditions when using an array detector, we will want the mapping between the array-detector pixel and display pixel to be one-to-one (1:1). That is, the size of the image of the display pixel is the same size as the detector pixel.

3.3 Display Setup and Specmanship

Please note: This time, we are not going to allow manufacturer setup if such setup conditions in any way makes the display unsatisfactory in its performance as would be judged by trained observers. No more of this tweaking the display controls to give the best readings when those readings are not realistic settings for the intended uses, again, as



would be judged by expert viewers not from the company that manufactures the display. We are taking this position for the benefit manufacturers that strive hard to make quality devices in order to protect them from the unscrupulous.

Setting up a display means to adjust the available controls to achieve the best image as would be judged by an expert reviewer or trained observer. There are two general methods to set up a display, either in (1) an ambient lighting environment or (2) in a darkroom. The problem with using an ambient environment is that that illuminating surround must be carefully specified and reproducible, which is often difficult to achieve. Keep in mind that the eye is a non-linear detector whereas our measurement equipment is linear. A small change to our eyes can be a significant change as measured by our instruments. Small changes in the ambient environment can have a significant impact on our measurements yet be undetectable by our eyes. The types of ambient environments that can yield reproducible are discussed in the Chapter 12 Reflection Measurements; there we discuss what constitutes a robust measurement apparatus and provide appropriate warnings should certain apparatus not provide reproducible results with ease.

3.3.1 SpecsmanSHIP & Wiggle-Room Elimination

SpecsmanSHIP amounts to deliberately misleading people by providing specifications that do not realistically portray the display characteristics under normal use. The term “wiggle-room” arises from a lack of absolute precision in the language used in specifying a requirement where the readers know exactly what is really meant by the requirement, but because of the lack of precision of the language, they deliberately find a loophole in the requirement or deliberately misinterpret the requirement to their own advantage. It can amount to a form of specsmanSHIP.

If the manufacturer describes or specifies how to set up the display for its intended use to provide the very best quality and most pleasing and useful image for the task at hand, then use the manufacturer’s setup specifications to set up the display. If the manufacturer’s setup specifications are not provided or are not suitable for the intended task then you should use the other suggestions presented in these sections. However, it is not permissible—and it violates the philosophy of this document—to adjust the display to extremes in order to get extreme measurement results if such adjustments make the display unsuitable, impractical, and unreasonable for the intended task, or drives it to extremes beyond the anticipated production and/or distribution configuration. Calling for such extreme settings disqualifies the manufacturer’s setup specifications from being used to set up the display. The term manufacturer’s setup specifications or any other idea presented in these sections is not a license for anyone tweaking the display to an impractical state and then obtaining measurement results for a public disclosure. That is, the display needs to look as good as it can for its intended task and not be configured with unrealistic settings that are used only to make the measurement results look good for competition or marketing purposes.

3.3.2 Inappropriate Mixing of Display Adjustments

There are situations where the display is intended to be adjusted to accommodate different surround conditions, and the display may therefore have different modes of operation. For example, automotive displays must operate in bright daylight yet be dimmed for night driving; as such, they can be characterized by a dimming ratio and can be run in different modes of luminance. Under such intended conditions, the display controls can be changed. However, the display must be characterized for each mode that is employed. It is not permissible to use different modes and mix the specifications simply to improve the apparent display’s specifications—that is specsmanSHIP and is not allowed in this document.

3.4 Patterns

Numerous test patterns are used throughout this document. Such patterns are available for download. See the Metrology Appendix A12 for a full explanation of the patterns. When driving a display with an analog signal, it is important to check the signal characteristics of, for example, an analog graphics card in a computer to be sure the levels are correct. Otherwise, we might be blaming the display for errors that the graphics card is making.



3.5 Display Setup and Adjustment

Ideally, we would want to see all the gray levels that are being sent to the display. For example, with an eight-bit display having the black level associated with gray level 0 and white associated with gray level 255, we would hope to be able to see the gray level 1 just slightly above black and the gray level 254 just slightly below white when the entire gray scale is produced on the screen. Of course, we would also want to see all the 256 levels distinguished properly. However, some displays cannot accomplish this because of various reasons or problems. The snaking gray shades pattern shown in FIGURE 3.3 is useful for visually checking the number of gray shades that the display can produce. Of course, this discussion assumes that the display you are measuring has the capability to be adjusted. This pattern is described in detail in the appendix: A12 Images and Patterns for Procedures.

Just seeing all or most of the gray levels between black and white is not enough; how that gray scale is rendered is also important. There are situations where we can see all the gray levels, but they may be too compressed together in one region of the gray scale and separated too much in another region. A good way to visually check to see if the full gray-scale rendering is adequate is to look at various scenes and especially faces—see FIGURE 3.4. The measurements of the gray scale are cared for in Chapter 6, Gray-Scale and Color-Scale Metrics, where attention is also given to how the gray scale changes chromaticity slightly from shade to shade. We describe three methods of adjustment below.

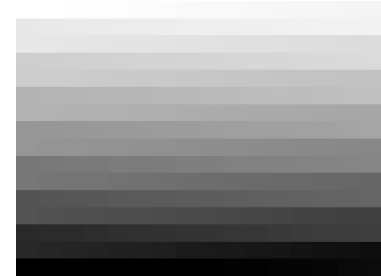
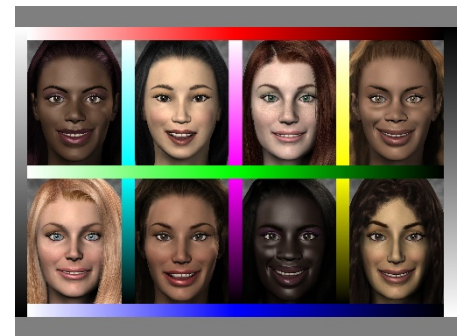


FIGURE 3.3. Snaking gray shades
SSW256_####x####.png



FIGURE 3.4. Static images of scenes and especially faces are ways to check if the gray scale is rendered properly. You may see a problem in a face image that is not discernible in a gray-scale ramp or color-scale ramp or even a natural scene. These and other images, including faces, are available for download at DOI [10.55410/LGAM8989](https://doi.org/10.55410/LGAM8989).



3.5.1 Ideal Darkroom Adjustment

Employ a pattern with black at an edge or corner but with content in the vicinity and elsewhere in the pattern as well as white—see FIGURE 3.5 for an example. We will first want to maximize the gray-shade range, if possible, then check the image quality after adjustment. Here is a procedure:

1. If the black level is adjustable, you will want to lower it to its lowest level or until it becomes invisible, but without losing the luminance of white and without losing the lower dark gray shades next to black (you don't want to drop out the dark gray shades).
2. The white level may then be adjusted for as bright as possible without losing the light gray levels and bringing up the black level.
3. If necessary, iteratively work between adjusting the white and black until the gray scale is perfected as much as possible.
4. Then look at images and face patterns, as in FIGURE 3.4, to see if they look correct. A quick measurement of the gray scale may be valuable as



FIGURE 3.5. Pattern with black at corner but with content elsewhere (50 % average pixel level). SCPL17_####x####.png



well (Chapter 6). Check to be sure that you have not adjusted any dark grays to black and light grays to white using the snaking-gray-shade pattern in FIGURE 3.3.

3.5.2 Ideal Adjustment Under Ambient Illumination

There are only a few ambient conditions that will yield reproducible measurement results. Just putting the display in an office environment or other poorly characterized room will *not* provide measurement results that are reproducible. It may look fine to the eye, but our linear instruments results are greatly affected by changes that we cannot see well with our eyes.

Viewing room conditions as specified by the various standards committees and groups may perform well for visual inspection of the display, but they do not necessarily serve well for good measurement purposes, depending upon the reflection properties of the display surface. In Chapter 11 Reflection Metrics we detail the types of ambient conditions that lead to reproducible measurement results, and we warn of the problems that can arise from less robust ambient arrangements. All of the ambient conditions specified in Chapter 11 are simple arrangements. Putting the display in a viewing room is not a simple surround condition.

Given that you have arranged for an ambient surround that will produce robust measurement results such as a good uniform diffuse surround (see section 11.1), then here is a procedure:

1. If the black level is adjustable, use a pattern that will allow you to see the various gray levels in the vicinity of black such as the pattern in FIGURE 3.5 above or FIGURE 3.6 below. You will want to change (increase or decrease) the black level so that it is invisible just below the visible ambient reflection luminance. Do not adjust the black too far so you lose the next gray level above black; you want that level to be visible in the ambient light reflection, if possible. You do not want to push the dark gray levels beneath visibility within the ambient reflection.
2. The white level may then be adjusted for as bright as possible without losing the light gray levels and bringing up the black level.
3. If necessary, iteratively work between adjusting the white and black until the gray scale is perfected as much as possible.
4. Then look at images and face patterns, as in FIGURE 3.4, to see if they look correct. A quick measurement of the gray scale may be valuable as well (Chapter 6). Check to be sure that you have not adjusted any dark grays to black and light grays to white using the snaking-gray-shade pattern in FIGURE 3.3.
5. The display would then be measured in a darkroom.
6. To account for an ambient surround, we would measure the display's reflection properties under strictly controlled ambient conditions, and then we would calculate the display's performance under controlled surround conditions based upon those reflection measurements coupled with the darkroom measurements. This is discussed in the Reflection Measurements Chapter (11).

3.5.3 Compromised Adjustment

Some displays are not able to render all the gray shades of the entire gray scale. Either some of the dark gray shades are rendered black or some of the light gray shades are rendered white or both. This is a compression of the gray scale. Measurements are sometimes needed to determine the actual gray scale; see Chapter 6 Gray-Scale & Color-Scale Metrics for specific measurement methods to characterize the gray scale. We are worried about the ends of the gray scale and how they are rendered in setting up the display unless a separate tone-rendering curve is provided. However, in all cases, the final check for a quality adjustment should be how it looks to the eye such as with imagery. The gray scale or color scale may be distorted or

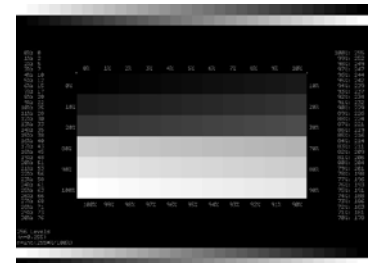


FIGURE 3.6. Pattern SEB01 with gray scale expressed in integer percentage.
SEB01_####x####.png



compressed, and the imagery may not look correct even though the ends of the gray scale are properly rendered and revealed by the above methods; this is a problem for Chapter 6.

3.6 Coordinate Systems and Viewing Angles

Cartesian coordinates and initial alignment conditions: This document adopts right-handed (x, y, z) Cartesian coordinates with the origin at the center of the screen. The z axis is perpendicular (normal) to the screen, the x axis is the screen horizontal, and the y axis is the screen vertical. The x and y axes lie in the plane of the display surface. We define the non-primed Cartesian system (x, y, z) as being attached to the display and the primed Cartesian system (x', y', z') as being fixed in the laboratory. FIGURE 3.7 shows the laboratory coordinates aligned with the display coordinates. The normal initial alignment between the display coordinates and the laboratory coordinates is when the z' axis is aligned with the z axis of the display and where the origins of the axes are separated by a known distance c_0 . In the figures that follow, the laboratory system will be shown as separated from the display under test (DUT). This is done to reduce the complexity of the figures.

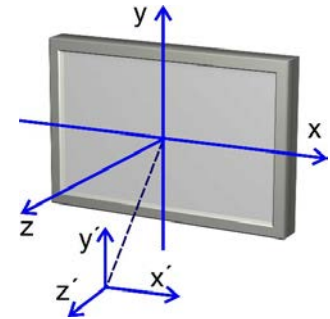


FIGURE 3.7. Display coordinates (unprimed) and laboratory coordinates (primed). Axes are shown not aligned.

Spherical coordinates: Associated with this Cartesian system is the spherical coordinate system (r, θ, ϕ) , where r is the radius from the center of the display coordinate system, θ is the inclination from the z axis (display normal, the polar axis of the spherical coordinate system), and ϕ is the counter-clockwise angle from the x axis in the xy plane (the display surface) as observed from the z axis (ϕ is a right handed rotation about the z axis starting at the x axis)—see FIGURE 3.8. Sometimes ϕ is called the axial angle. We represent the position of the observer or the LMD with a spherical featureless eye. The laboratory coordinates are shown attached to the eye.

Viewing angle coordinates: We define the horizontal θ_H and vertical θ_V viewing angles as the inclination angles of the viewing direction resolved into components in the horizontal xz plane and vertical zy plane respectively. FIGURE 3.9 shows that the viewing angles resolve the viewing direction into two angles measured from the z axis. Also note the rotation of the laboratory coordinates (attached to our eye) with the display coordinates.

This viewing-angle coordinate system is the most natural coordinate system for specifying the angle of view. It is the one we are thinking about when we look at displays from various angles. However, throughout most of the literature we find the use of the spherical-coordinate system. Also note that these viewing angles are not the same as the angles associated with goniometric systems in common use today—see the next section.

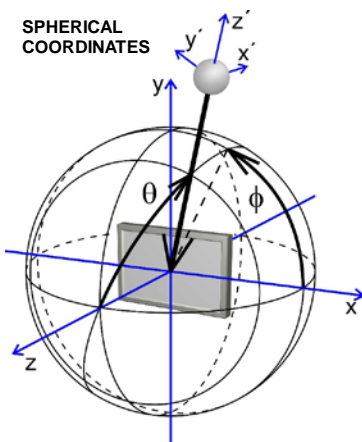


FIGURE 3.8. Spherical coordinates.

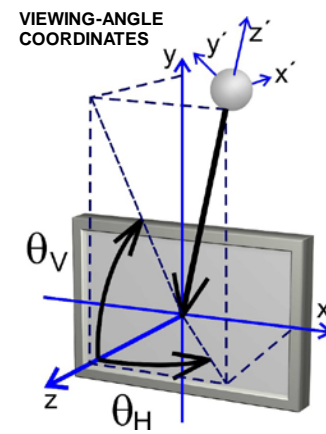


FIGURE 3.9. Horizontal and vertical viewing angles used in this document.



Goniometric configurations: In our following illustrations, a goniometer is an apparatus that rotates the object under study relative to the detector where some point relative to the object (the center of the screen, for example) remains fixed in space (the axes of rotation go through the same point). This can also be accomplished by rotating the light-measuring device (LMD) about the display under test (DUT), or conversely, by rotating the DUT while the LMD stays fixed as we illustrate here. When the goniometer has two orthogonal rotational axes, one axis rotates with a rotation of the other axis. (A mirror gimbal mount is an example.) The axis that remains fixed is the independent axis. The axis that rotates about the independent axis is the dependent axis. There are two very common goniometer configurations that we describe below: north polar and east polar. The configurations shown tilt the display. Such systems assume that the direction of gravity and the direction of the earth's magnetic field have no effect on the display performance. These are by no means the only goniometric configurations that are possible. The equations shown in the following relate the viewing-angle coordinates, the north-polar (FIGURE 3.10), and the east-polar (FIGURE 3.12) goniometric coordinate systems to the Cartesian and the spherical coordinate systems. These equations do not necessarily apply in all goniometric configurations.

North polar goniometric coordinates, independent axis horizontal: In this case, the independent axis of the goniometer is horizontal, and the orthogonal (dependent) axis is rotated about the horizontal axis in a vertical plane. FIGURE 3.10 shows the goniometer aligned with the laboratory axes. Note the hemisphere on the surface of the display. The circular arcs on that sphere are traced out by the stationary z' axis of the laboratory frame of reference as the display is rotated about the goniometer axes. FIGURE 3.11 shows an arbitrary viewing angle resolved into a horizontal rotation ν_H about the y axis (a right-handed rotation about the vertical y axis) and a vertical rotation ν_V about a horizontal axis in the xz plane toward the y axis. It is important to recognize that the rotational coordinates we are using here are defined relative to the coordinate axes attached to the screen. If we were to illustrate the display orientation indicated in FIGURE 3.11 using the goniometer in FIGURE 3.10, the display (its normal) would be pictured as being rotated to the left and then down. The angles ν_H and ν_V appear as opposite rotations in FIGURE 3.10 compared to the rotations pictured in FIGURE 3.11. This is because we are looking at the rotations from the viewpoint of the display in FIGURE 3.11 and from the laboratory in FIGURE 3.10.

East polar goniometric coordinates, independent axis vertical: In this case, the independent axis of the goniometer is vertical, and the orthogonal (dependent) axis is rotated about the vertical axis in a horizontal plane. FIGURE 3.12 shows the goniometer aligned with the laboratory axes. The circular arcs on the hemisphere on the display surface are traced out by the stationary z' axis in the laboratory frame of reference as the display is rotated about the goniometer axes. FIGURE 3.10 shows an arbitrary viewing angle resolved into a horizontal rotation about the y axis ε_H (a right-handed rotation about the vertical y axis) and a vertical rotation about the x axis ε_V (a left-handed rotation about the x axis). Again, these coordinates are referenced to the screen coordinate system. The display orientation shown in FIGURE 3.13 using the goniometer in FIGURE 3.12 would show the display (its normal) rotated to the left and then down. The angles ν_H and ν_V appear as opposite rotations in FIGURE 3.12 and FIGURE 3.13, because we are looking at the rotations from the viewpoint of the display in FIGURE 3.13 and the laboratory in FIGURE 3.12.

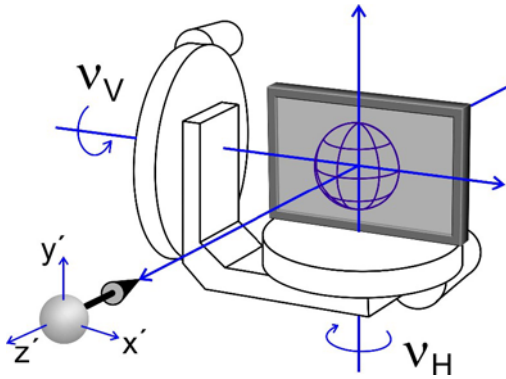


FIGURE 3.10. North polar goniometer with independent axis horizontal.

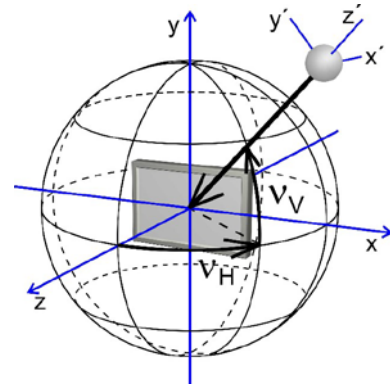


FIGURE 3.11. North polar goniometric coordinates relative to the surface of the display.

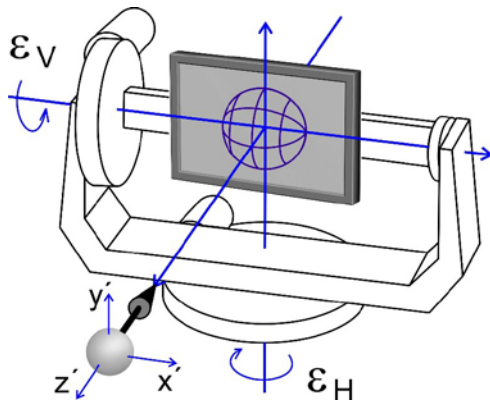


FIGURE 3.12. East polar goniometer with independent axis vertical.

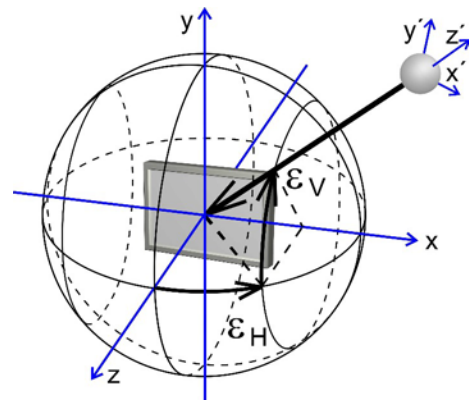


FIGURE 3.13. East polar goniometric coordinates relative to the surface of the display.

In efforts to make it clear that the three coordinate systems are not the same, note FIGURE 3.14 where we indicate the same viewing direction in the three horizontal-vertical coordinate systems described above: the horizontal-vertical viewing angle coordinates, the north-polar coordinates, and the east-polar coordinates. The horizontal viewing angle is the same as the north-polar horizontal rotation angle, and the vertical viewing angle is the same as the east-polar vertical rotation angle:

$$\begin{aligned} \theta_H &= \theta_V \\ \theta_V &= \varepsilon_V \end{aligned} \quad (3.1)$$

The equations expressing the relationships between these coordinate systems and with the spherical coordinate system can be derived by resolving into Cartesian coordinates an arbitrary vector expressed in terms of these display coordinate systems, then requiring that the respective x, y, z components be equal. TABLES 3.2 and TABLE 3.3 show all the coordinate transformations for the five coordinate systems used. The more useful ones are highlighted with a thick-lined box. We recommend that spherical coordinates be used in the final reporting, or at least the viewing angle coordinates be used to avoid confusion.

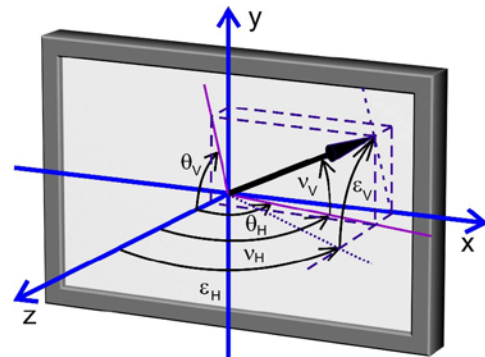


FIGURE 3.14. A viewing direction (heavy black arrow) resolved into the three horizontal-vertical angular coordinate systems.



Chapter 3 – Setup of Display and Apparatus

TABLE 3.2. Coordinate transformations.
 $\arcsin \theta \equiv \sin^{-1} \theta$, $\arccos \theta \equiv \cos^{-1} \theta$, $\arctan \theta \equiv \tan^{-1} \theta$, $0 \leq \theta \leq \frac{\pi}{2}$

$\downarrow \Rightarrow$	Horizontal and vertical viewing angle $\theta_H, \theta_V = \text{hor.}, \text{ver.}$	North polar $\nu_H, \nu_V = \text{hor.}, \text{ver.}$ (Independent axis horizontal)	East Polar $\varepsilon_H, \varepsilon_V = \text{hor.}, \text{ver.}$ (Independent axis vertical)
Cartesian (Figure 3.7) x, y, z	$x = r \sin \theta \cos \varphi$ $y = r \sin \theta \sin \varphi$ $z = r \cos \theta$. Use spherical θ, φ as below box.	$x = r \sin \nu_H \cos \nu_V$ $y = r \sin \nu_V$ $z = r \cos \nu_H \cos \nu_V$	$x = r \sin \varepsilon_H$ $y = r \cos \varepsilon_H \sin \varepsilon_V$ $z = r \cos \varepsilon_H \cos \varepsilon_V$
Spherical (Figure 3.8) θ, φ	$\theta = \tan^{-1} \sqrt{\tan^2 \theta_H + \tan^2 \theta_V}$ $\varphi = \tan^{-1} \left(\frac{\tan \theta_V}{\tan \theta_H} \right)$	$\theta = \cos^{-1} (\cos \nu_V \cos \nu_H)$ $\varphi = \tan^{-1} \left(\frac{\tan \nu_V}{\sin \nu_H} \right)$	$\theta = \cos^{-1} (\cos \varepsilon_V \cos \varepsilon_H)$ $\varphi = \tan^{-1} \left(\frac{\sin \varepsilon_V}{\tan \varepsilon_H} \right)$
Horizontal and vertical viewing angle (Figure 3.9) θ_H, θ_V	1	$\theta_H = \nu_H$ $\theta_V = \tan^{-1} \left(\frac{\tan \nu_V}{\cos \nu_H} \right)$	$\theta_H = \tan^{-1} \left(\frac{\tan \varepsilon_H}{\cos \varepsilon_V} \right)$ $\theta_V = \varepsilon_V$
North polar (Figure 3.10) ν_H, ν_V	$\nu_H = \theta_H$ $\nu_V = \tan^{-1} (\tan \theta_V \cos \theta_H)$	1	$\nu_H = \tan^{-1} \left(\frac{\tan \varepsilon_H}{\cos \varepsilon_V} \right)$ $\nu_V = \sin^{-1} (\cos \varepsilon_H \sin \varepsilon_V)$
East Polar (Figure 3.11) $\varepsilon_H, \varepsilon_V$	$\varepsilon_H = \tan^{-1} (\tan \theta_H \cos \theta_V)$ $\varepsilon_V = \theta_V$	$\varepsilon_H = \sin^{-1} (\cos \nu_V \sin \nu_H)$ $\varepsilon_V = \tan^{-1} \left(\frac{\tan \nu_V}{\cos \nu_H} \right)$	1



You think you're confused! It took us weeks to get this worked out!

TABLE 3.3. Coordinate transformations.

$\downarrow \Rightarrow$	Cartesian x, y, z $r = \sqrt{x^2 + y^2 + z^2}$	Spherical θ, φ
Cartesian (Figure 3.7) x, y, z	1	$x = r \sin \nu_H \cos \nu_V$ $y = r \sin \nu_V$ $z = r \cos \nu_H \cos \nu_V$
Spherical (Figure 3.8) θ, φ	$\theta = \cos^{-1} \left(\frac{z}{r} \right)$ $\varphi = \tan^{-1} \left(\frac{y}{x} \right)$	1
Horizontal and vertical viewing angle (Figure 3.9) θ_H, θ_V	$\theta_H = \tan^{-1} \left(\frac{x}{z} \right)$ $\theta_V = \tan^{-1} \left(\frac{y}{z} \right)$	$\theta_H = \tan^{-1} (\tan \theta \cos \varphi)$ $\theta_V = \tan^{-1} (\tan \theta \sin \varphi)$



North polar (Figure 3.10) ν_H, ν_V	$\nu_H = \tan^{-1} \left(\frac{x}{y} \right)$ $\nu_V = \sin^{-1} \left(\frac{y}{r} \right)$	$\nu_H = \tan^{-1} (\tan \theta \cos \varphi)$ $\nu_V = \sin^{-1} (\sin \theta \sin \varphi)$
East Polar (Figure 3.11) $\varepsilon_H, \varepsilon_V$	$\varepsilon_H = \sin^{-1} \left(\frac{x}{r} \right)$ $\varepsilon_V = \tan^{-1} \left(\frac{y}{z} \right)$	$\varepsilon_H = \sin^{-1} (\sin \theta \cos \varphi)$ $\varepsilon_V = \tan^{-1} (\tan \theta \sin \varphi)$

3.7 Variables and Nomenclature

Luminance meter nomenclature: Here we show a viewport luminance meter, but any detector that uses a viewport and lens to measure light has the same nomenclature: spectroradiometer, radiometer, etc.

The acceptance area (and associate angular aperture) is not always defined by the diameter of the focusing lens and is not always located at the position of the front of the lens. An internal port (entrance pupil) may define a different position. The bottom figure shows a thin lens ray trace of a luminance meter using blue and pink lines: Rays parallel to the lens axis go through the focus and rays going through the center of the lens are unperturbed. Such ray traces are only approximations.

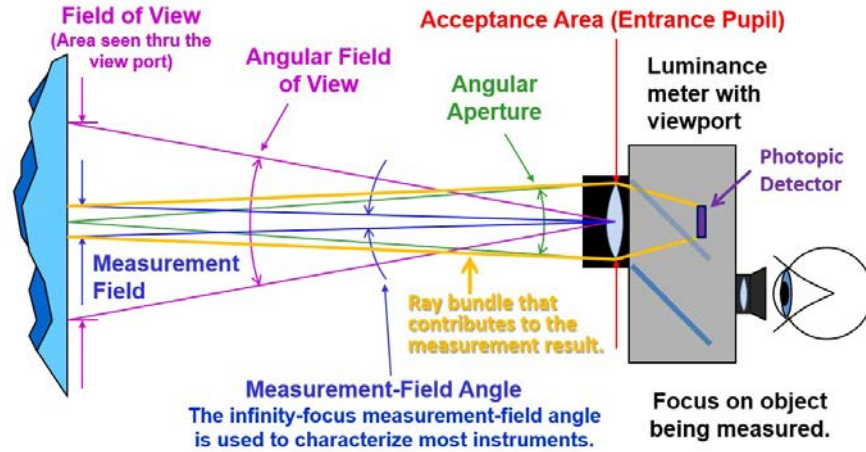


FIGURE 3.15. Measurement field angle characterized at infinity focus.

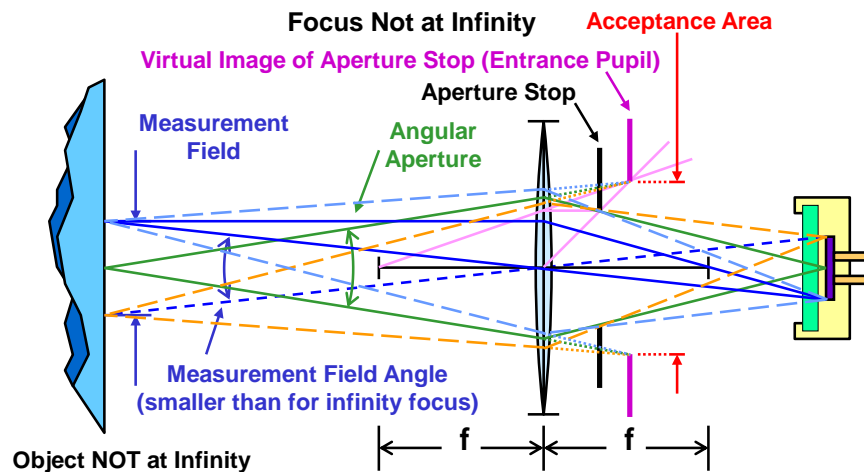


FIGURE 3.16. Measurement field angle at DUT focus.



Variables: We are trying to specify variables for use in all facets of display metrology. The number of variables needed is rather daunting and our using them consistently throughout the document is not guaranteed. Nevertheless, the next two pages list some of the variables needed.

TABLE 3.4. Variables used in this document (partial listing)

Abbreviations: LMD = light-measurement device or detector; MF = measurement field; MFA = MF angle; subpixel subscript i = red, green, blue, (R,G,B), for example; subscript j = bit or voltage level number.

Symbol	Description	Symbol	Description
α	aspect ratio ($\alpha = HV^{-1}$), measurement-field angle	N_V	number of pixels in the vertical dimensions
a	small area, or small area of the screen	π	$3.141592653 \dots = 4 \tan^{-1}(1)$
A	Area	P	square pixel pitch (distance per pixel), power in watts (W), pressure
B	bidirectional reflectance distribution function (BRDF)	P_H	horizontal pixel pitch
c_d, c_s	distance from center of screen to detector, source	P_V	vertical pixel pitch
C	Contrast C = luminance ratio, C_m = Michelson contrast	q	luminance coefficient
D	diagonal measure of the rectangular viewable display pixel surface that contributes to the display of information, also density, diameter	Q	cluster defect dispersion quality (1/cluster density); also, a color W = white, R = red, G = green; B = blue; C = cyan, M = magenta, Y = yellow, K = black, S = gray shade.
$\nu_H, \nu_V, \varepsilon_H, \varepsilon_V$	north-polar and east-polar goniometer angles	R	refresh rate, radius
η	luminous efficacy (of a source), north-polar goniometric coordinate	ρ	reflectance factor
ε	frontal luminance efficiency, east-polar goniometric coordinate	r, r_a	radius, radius of round small area a on the screen
$E, E(\lambda), E_\lambda$	illuminance ($\text{lx} = \text{lm m}^{-2}$), spectral irradiance ($\text{Wm}^{-2}\text{nm}^{-1}$)	s, s_i	subpixel areas, small areas, distances, size of edge of square
f	fractional fill-factor threshold luminance	P	surface areas; signal level, or signal counts (as with using an array detector); also, square pixel spatial frequency (pixels per unit distance, $S = P^{-1}$)
f_a	fractional (or percent) area of the screen for small area, target, or measurement field (MF)	S_H	horizontal pixel spatial frequency
$\Phi, \Phi(\lambda), \Phi_\lambda$	luminous flux (lm), spectral radiant flux (Wnm^{-1})	S_V	vertical pixel spatial frequency
H	horizontal size of the active area of the screen	θ, ϕ	spherical coordinates
\mathcal{H}	Halation	θ_H, θ_V	horizontal, vertical viewing angles
h	haze peak	θ_F	measurement field angle (MFA) of LMD or detector
γ	exponent in the power function when it can be used to describe the electro-optical transfer function	t	elapsed time, time
$I, I(\lambda), I_\lambda$	luminous intensity ($\text{cd} = \text{lm sr}^{-1}$), spectral radiant intensity ($\text{W sr}^{-1}\text{nm}^{-1}$)	T_C	correlated color temperature
k	integer, or detector conversion current per flux, <i>e.g.</i> , A lm^{-1} , or $\text{A W}^{-1}\text{nm}^{-1}$	V, V_j	vertical active area of the screen size, voltage, gray levels, volume



K_i, K	luminance (cd m^{-2}), radiance ($\text{W sr}^{-1}\text{m}^{-2}\text{nm}^{-1}$)	W, W	weight, symbol for watt
λ	wavelength of light	Ω, ω	solid angle
L^*	lightness metric in CIELUV and CIELAB color spaces	x, y, z	Cartesian right-handed coordinate system with z perpendicular to the screen, x horizontal, y vertical
\mathcal{L}	Loading, index for left view in stereoscopic displays	u', v'	1976 CIE chromaticity coordinates
m	integer, mass	u, v	1960 CIE chromaticity coordinates (obsolete)
$M, M(\lambda)$ M_λ	luminous exitance ($\text{lx}=\text{lm m}^{-2}$), spectral radiant exitance ($\text{W m}^{-2}\text{nm}^{-1}$)	x, y	CIE 1931 chromaticity coordinates
N_a	number of pixels covered by a small area a	X, Y, Z	1931 CIE tristimulus values
N_T	total number of pixels ($N_T=N_H \times N_V$)	$\bar{x}(\lambda),$ $\bar{y}(\lambda),$ $\bar{z}(\lambda)$	1931 CIE color matching functions
N_H	number of pixels in horizontal dimension		

TABLE 3.5. Variables and detector parameters used in this document (partial listing).

The detector when looking through a view port will be centered in that view port and held sufficiently far away from the view port so that it is not affected by veiling glare from bright areas. Not all parameters are independent.

Symbol	Description	Symbol	Description
v_d, ν_d, ψ_d	pitch (about the x axis), roll (about the z axis), and yaw (about the y axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane - see target position (x_t, y_t) . The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y -axis is pointing upward. Sometimes ψ is used as a detector subtense when not used as a yaw angle.	x_t, y_t	Position where the detector is pointing or target position of detector in the xy plane at which the detector is pointing. These can also be described using pitch, roll, and yaw angles (v_d, ν_d, ψ_d) from the ideal position with respect to the radius vector to the center and the horizontal plane.
c_d	distance of the center of the detector front surface (or lens) from the center (often z_d when detector is on the optical axis)	F	The point at which the detector is focused (if so equipped). It can be a discrete variable as in either focusing on the source or the display, or it can be a continuous variable where it is focused at some point along its optical path.
ϕ_d	Rotation or axial angle of the detector about the z axis starting from the x axis and going counter-clockwise	κ_d	subtense of the entrance pupil of the detector or angular aperture, $\tan 0.5\kappa_d = R_d c_d^{-1}$
R_d	radius of the entrance pupil of the detector	θ_d	inclination angle of detector from the z axis
α	measurement field angle		



TABLE 3.6. Source parameters (also filter parameters using subscript “f”). Not all parameters are independent.

Symbol	Description	Symbol	Description
c_s	distance of center of the source exit port from the center of coordinate system (often z_s when the source is on the geometrical z axis)	κ_s, ψ_s	subtense of source from the center (ψ_s is sometimes used when a roll specification is not employed), $\tan 0.5\kappa_r = R_s c_s^{-1}$
x_s, y_s	target position of source in the xy plane at which the normal of the source exit port is pointing. These can also be described using pitch, roll, and yaw angles (ν_s, ν_s, ψ_s) from the ideal position with respect to the radius vector to the center and the horizontal plane.	ν_s, ν_s, ψ_s	pitch (about the x axis), roll (about the z axis), and yaw (about the y axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_s, y_s). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y axis is pointing upward. Sometimes ψ is used as a source subtense when not used as a yaw angle.
ϕ_s	rotation or axial angle of the source about the z axis starting from the x axis and going counterclockwise	For sources with view ports in the back side through which measurements are made:	
R_s	radius of the source exit port (outer diameter of ring light source)	R_v	radius of the view port
w_s	width of ring light source	d_v	distance of the view port from the exit port of the source
θ_r	angle of ring light outer diameter from normal or angle of outer diameter edge of the exit port of a source positioned close to the display as measured from the normal, $\tan \theta_r = R_s C_s^{-1}$	c_v	distance of the view port from the center
θ_s	inclination angle of the source from the z axis	κ_v	subtense of view port from the center, $\tan 0.5\kappa_v = R_v c_v^{-1}$
U_s	average uniformity of the source luminance over the full extent of the exit port	θ_v, ϕ_v	angles of the view port from the exit port center or from the normal of the display as with the diffuse illumination measurement (as defined for similar angles above)

REFERENCES

- [3.1] Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns in K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, pp. 7.1-7.56). New York: Wiley
- [3.2] *The Encyclopaedia of Medical Imaging*, H. Pettersson, Ed., p. 199. Taylor & Francis, UK, 1998.



4. Visual Assessment

Especially during warm up of the display it is a good time to visually inspect its performance. Here are a few ways that its quality can be assessed visually. A variety of patterns are employed to make these assessments. Although the ICDM supplies patterns in different formats for these and other purposes, companies make software that will provide such patterns to perform this kind of assessment, where the software tailors the pattern to the display by reading its pixel array electronically.

During the 20-minute warm up period (or whatever period is required for warm-up) certain subjective observations can be made. Also, any controls on the DUT can be set to provide the best images or patterns commensurate with the use of the display and its task setting (consistent with the manufacturer's specifications, if they exist or apply)—see the previous chapter on setup of the display.

The section on subjective evaluations allows for a visual check to determine the presence of certain display conditions or anomalies and give guidelines to help determine the level of seriousness of problems. With the exception of the Saturated Colors (4.1), presence of any of these conditions is usually undesirable and degrades the quality of displayed video or the appearance of the display. Some displays will have some of these characteristics, and some will not.

All of the tests are made by human visual observation with no measurement equipment, unless specifically stated within a test. There may be visual enhancement aids, such as magnifiers or optical filters, which can assist the evaluations. It is important to note that visual testing infers looking for visual problems which may or may not be present rather than measuring performance as is done for the regular testing sections of this standard. Saturated Colors (4.1) is the exception. For color displays, the colors are expected to be present. Absence of the colors or video artifacts on the way the colors are displayed would suggest a serious problem. It is recognized that subjective evaluations depend upon the observer. For example, some people exhibit a much greater sensitivity to flicker than others. These evaluations are intended to flag the most obvious problems.

Should any of the tests of this section not be completed during the warm-up interval, they may be tested at any time thereafter. It is assumed all tests in this section are immune to warm up time, and that the order of the tests is during warm up is not a factor. Should any of these tests be deemed to dependent upon warm up time, they should be conducted after proper warm up time has been achieved.



4.1. Saturated Colors

Use the color bar pattern to determine the presence of all saturated and primary colors. No measurements are made, so only the presence of the colors is observed, not an assessment of how well the colors are reproduced. The full-screen color bar pattern is intended for visual assessment of the general color performance of a display. All colors are saturated to enable minimum difficulty in visually assessing presence of color and relative saturation as per an adequate color gamut. The full-screen color gamut is measured in 5.1.4.

The full-screen color bar pattern (FIGURE 4.1) is a sequence of vertical bars that show the three saturated primary colors, three secondary, black, and white. The color order (from left to right) is white, yellow, cyan, green, magenta, red, blue, and black—this assumes an RGB color scheme. Their order represents video content luminance



from maximum on the left, to minimum, on the right. Their heights are full screen with widths of 1/8 of the total horizontal video size.

Use of Color Bars: There are a number of uses for which the color bar pattern will serve to check:

- the saturated-color (full gamut) and black-and-white performance of the DUT
- to assure all primary and secondary colors are displayed
- to assure all colors are in the correct order
- of proper signal path arrangement, including wiring and cabling
- the color purity, saturation, and hue
- the spatial color separation
- of signal path performance for adequate color response capability
- to assure that all saturated colors can be displayed without overlap or other spatial degradation
- to assure all colors are distinct from each other
- to assure there are no color dependencies or characteristics of the DUT that vary from one color to another.

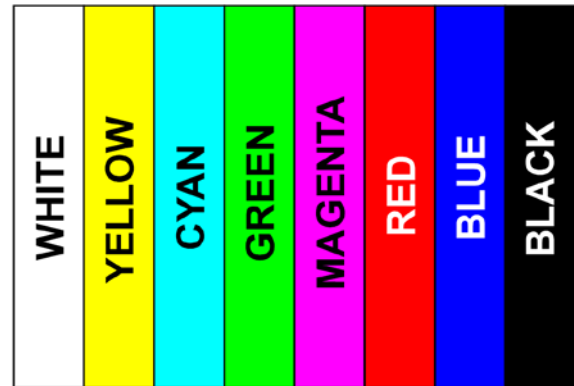


FIGURE 4.1. Color bar pattern from RGB primaries.

REPORTING

Report in the comments sections of the reporting templates any problems with the appearance of normally displayed color bars, such as missing colors, wrong colors, problems at the transition points between colors, or color artifacts, etc.

4.2. Cosmetic Defects

While displaying alternately a white and black full screen, inspect the DUT for cosmetic defects. These are imperfections of the display surface or its packaging that are visible on the external surface that detract from the display's value such as the following examples (not a complete or required list)

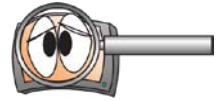
cuts	gouges	pullouts	misalignment of parts
dents	scratches	cracks	stains on components
smears	bubbles	bumps	other ...

Report description of any unacceptable cosmetic defects on the reporting sheet in the comment section along with any other appropriate information such as position, type of defect, size, and shape. Note

This section does not include pixel defects that are handled separately in 4.4 nor does it include mura (nonuniformities on the display surface) dealt with in 4.3.

DISCUSSION

This is an example of a characteristic that may or may not exist on a display face or its enclosure. Such defects arise from contamination in the manufacturing process, cuts, scratches, gouges, etc., which could occur in any level of processing or handling of the product. All types of cosmetic defects cannot be easily classified. They vary almost limitlessly in types, characteristics, and conditions, and what is acceptable or not is generally determined in agreements between display manufacturers/handlers and those who integrate them into usable products, such as OEM's. It is beyond the scope of this document to offer a defined procedure of or listing for cosmetic defects. Other



than the general guidelines, cosmetic defect assessment should be done in accordance with agreed upon guidelines between the display supplier and user.

In general, cosmetic defects can be any type of abnormalities found on a display, housing, front of screen, etc. They may be assessed in terms of quantity, size, shape, level of visibility, location, etc. They may or may not degrade the performance and the usability of the display, and how objectionable they are may be related to the area where they are located or their proximity to boundaries on the display or to other defects. For instance, a highly visible cut, gouge, or permanent stain on the face of a display might significantly reduce visibility and reduce the usability of the display, whereas an even worse cut, scratch, etc. on the side or rear of the display would not affect the visible display area at all and might be acceptable. The acceptability of either must be determined by the observer based upon specific criteria from the interested parties.

4.3. Mura

Mura is a Japanese term meaning *blemish* and has been adopted in English to provide a name for imperfections of the display pixel matrix surface(s) that are visible when the display is in operation. Inspect the display surface while displaying a white full screen, a black full screen, and a dark gray full screen. Look for any imperfections that interfere with the uniformity of the displayed luminance such as a mottled appearance or bright or dark spots that may be objectionable. This is not attempting to look for large area nonuniformities which will be measured in Chapter 8, Uniformity Measurement, but attempts to find any imperfections which are present on the scale of from a few pixels in size to usually less than 20 % of the screen diagonal. Report any findings in terms of size, quantity, position, etc., in the comment section of the reporting sheet.

4.4. Pixel Defects

NOTE: The tolerance for pixel defects should be negotiated between all interested parties. The pixel defect tolerance depends upon the application of the display, and a general classification scheme cannot cover all specialized uses of displays. A possible method of pixel defect characterization and identification that may be of use to you is presented as a measurement in 8.7 Defective Pixels. During warm-up is an excellent time to look for bad pixels.

4.5. Flicker Visibility

With a white full screen (or whatever pattern is determined to produce the worst-case flicker) and the DUT in a typical office lighting situation (or the ambient lighting which is characteristic of the environment in which the display will be used), look for flicker from the display surface with the screen in your foveal and then in your peripheral vision. Report any observed flicker and observing conditions on the reporting sheet, *e.g.*, the pattern displayed, the colors employed, size of displayed area, observer viewing angle, if peripheral or foveal vision is used to observe the flicker, ambient lighting, viewing distance, etc.

DISCUSSION

Flicker is the visible rapid luminance variations in time having to do with how the screen is driven to produce a static image. Flicker is defined as perceptible rapid temporal luminance variation of a nominally constant-luminance test pattern: Flicker can be analytically measured, as in Chapter 12, but unless the measured flicker level exceeds the minimum human perception threshold, the DUT cannot properly be said to be flickering. A number of characteristics affect the perceptibility of flicker luminance level, frequency, modulation, ambient lighting, displayed area, whether the displayed area is in foveal or peripheral vision. Note that there is a wide variation in observer sensitivity to flicker—flicker may be noticeable to one person but imperceptible to another. Any temporal luminance modulations invisible to all human observers are not of concern here. The presence of visible flicker on a display is generally undesirable, but some level of flicker may be acceptable in certain cases. All interested parties should agree with the acceptability and conditions of visible flicker.



The characteristics that determine the production of flicker will vary from technology to technology. For example, some technologies have little persistence of luminance from frame to frame, and higher vertical refresh rates, *e.g.*, 76-85 Hz, rather than 60 Hz, are required to minimize perception of flicker. For such technologies, higher luminance levels increase the perception of flicker, while higher vertical rates reduce it. Other displays have dependencies that can cause flicker at reduced luminance levels and/or reduced refresh rates. This section does not intend to go into great detail about the properties of flicker or visible perception variables. For measurements of flicker see Chapter 12.

4.6. Artifacts and Irregularities

While displaying a variety of full-screens saturated colors, pastels, white, grays, or black, as well as other patterns like checkerboards, grilles, etc.; look for video artifacts such as noise, periodic spatial irregularities (Moiré), or periodic temporal irregularities. Report any inadequacies in the comment section of the reporting sheet.

DISCUSSION

Displays can be characterized and measured in every conceivable manner, yet the possibility of some non-quantified visible artifact can still exist. There seem to be an indeterminable number of possibilities on how video artifacts can occur and what their characteristics may be. They may relate to any display anomalies or part of any of the electronics that generate video for the DUT or other sources coupling into the video electronics generation. Non-electronic mechanisms or electronic sources outside of the system to which the DUT belongs may also cause video artifacts. Examples could include magnetic coupling or radio frequency susceptibility. It should be kept in mind that the DUT itself does not have to have susceptibility to such mechanisms, but rather the signal paths in proximity to the DUT, such as a video signal transmission line, could allow for external coupling, and then directly transmit it to the DUT where it might be shown as unwanted video.

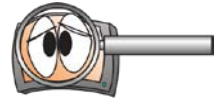
Visible video artifacts can be dynamic or moving in time incoherently with the video signal. It is also possible to have video artifacts that are stationary or synchronous with the video or part of the video. These video artifacts may also be present on all of the screen or part (or parts) of it, and they might even vary as a function of position. They might also be sensitive to video content, changing or only occurring for certain variations of displayed video. They might be of any size, location, pattern, of any temporal or spatial characteristics, and may occur consistently or may be intermittent, appearing to be entirely random. Due to the potential randomness of such characteristics, it is impossible to produce all situations for the DUT in which artifacts might occur, and there might never be any artifacts in the DUT. Observed video artifacts are often classified as video noise, an unwanted part of the video signal. Whatever the cause, this section permits the documentation of any visual artifact on the DUT. To further complicate matters, subtle artifacts may be perceivable by one observer but be invisible to another.

SETUP

There is no one best video pattern or condition that should be used to seek video artifacts. The only guidelines that can be given are to use whatever video and external stimuli that may be useful, typical, or practical to implement. Basic operation for observing video artifacts would include starting testing by using patterns such as all white, all black, fine checkerboards (down to alternating black-white pixels), vertical lines, horizontal lines, and variations of color (both saturated and pastel) and gray-scale content and position.

PROCEDURE

Using any number of different patterns, vary any condition of the DUT to observe video artifacts. Vary any external stimuli as appropriate and with minimal risk of damage to the system. Some examples of external stimuli (use with caution) might be movement of video lines (if accessible), variation of the power source within its tolerance limits (if



accessible), movement of the DUT, lightly nudging connectors, variation of any controls like brightness or contrast, etc.

REPORTING

Any pattern, condition, or external stimulus that induces, changes, or eliminates video artifacts should be reported. Also, report the description and any other pertinent characteristics of any perception of video noise on the reporting sheet. Other characteristics may include size, duration, position, or persistence of the disturbance. Report any artifact observations in the comment section of the reporting form.

COMMENT

See 8.2.3 Mura Analysis for a specific measurement example for mura.

4.7. Alternating Pixel Checkerboard

Display an alternating-pixel checkerboard pattern and look for clarity of black and white individual pixels. If the black pixels are gray or the white pixels are noticeably gray or both, it could indicate problems in some of the circuits or the generating signal. Report any inadequacies in the Comments Section of the reporting form.

DISCUSSION

An alternating pixel pattern is a series of on-off-on-off... pixels, *e.g.*, white-black-white-black..., where each successive row is the inverse of the row above it. Such a pattern is the same as a checkerboard pattern in which the size of the checkers is reduced to one pixel. A complement or inverse alternating pixel display may also be used whereby the two patterns can be compared.

Alternating pixel patterns produces the highest frequency video (equal to $0.5 \times$ the pixel clock rate), and pixel clarity on the DUT is representative of the display's ability to reproduce the highest frequency video signal. Such a pattern tests the DUT sensitivity to rise/fall times and frequency capabilities of the video system (generated video and transmission path). Some find that this pattern also enables them to check for pixel defects as well; any pixel which is continually fixed at a certain luminance level or color will often stand out better when observed surrounded by all black or white pixels.

4.8. Convergence

With some display technologies, such as CRTs, projection displays, etc., there is a possibility that the color components, *e.g.*, RGB, do not arrive at the same place on the display surface. How well the colors combine at the same place is called convergence. Convergence can be visually assessed by displaying a single-pixel grid of horizontal and vertical lines at a separation of 5 % of the screen's horizontal H and vertical V dimensions. Any misconvergence is visible as color edges to the white line or even a complete separation of the color components of

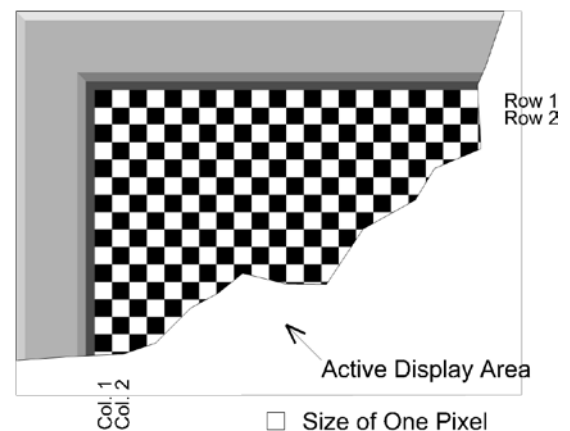


FIGURE 4.2. Alternating pixel pattern.

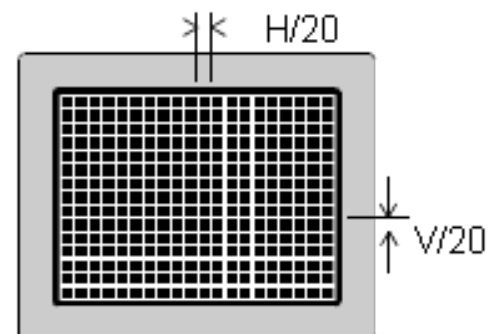


FIGURE 4.3. Pattern for convergence measurement.



the line. See 13.3.1 Convergence for a measurement method for the misconvergence.

4.9. Color and Grayscale Inversion

The pattern CINV01 is designed to reveal both color and gray-scale inversions and both color inversions, rotations, and confluences. See the appendix, A12 Color and Gray-Scale Inversion Target. It is available at DOI:[10.55410/lgam8989](https://doi.org/10.55410/lgam8989).

4.10. JND-Based Setup Alternative

When setup based on an objective visibility specification is desired, the following procedure is useful, based on a Just Noticeable Difference (JND) metric, *e.g.*, the NEMA DICOM gray scale described in B32. Such a gray scale, based on human distinguishability of gray shades, is used to control the luminance (or, for projectors, illuminance) step size between adjacent gray shades in a special gray-scale test pattern. Two specific step sizes (near white and near black) are adjusted through the “brightness” and “contrast” controls until adjacent block luminances in this test pattern lie within a specified JND range of each other.

First, set the black level (brightness control) so that the signal-level blocks on the top line, representing 0% and 5 % signal levels, are visible and distinct from each other, but not overly different from each other. A good criterion for distinctness is that the measured illuminance levels be between 2 and 20 JNDs on the gray scale. **NOTE:** In order to apply the metric to projection, the luminance values can be converted to illuminance units assuming a unity screen gain and a perfect Lambertian reflector.)

Next, reduce the video gain (contrast control) from maximum until each of the signal level blocks in the lower line of the pattern, representing the 95% and 100% signal levels, are visible and distinct from each other, but not overly different from each other. Again, visibility should be deemed as 2-20 JNDs for each illuminance step.

Repeat the above until neither procedure affects the meeting of the criterion by the other procedure; or, if this cannot be done, the best JND values between adjacent signal-level blocks shall be reported. Throughout the procedure, use the discriminability of signal-level blocks at 10%, 15%, 85%, and 90% for guidance and as a sanity check. **NOTE:** *Adjustment of the near-white and near-black gray levels does not guarantee conformance of the other gray shades to uniformity in JNDs.* See A12 Images and Patterns for Procedures for details of the patterns in FIGURE 4.5 used with black, gray (127/255), and white backgrounds as examples.

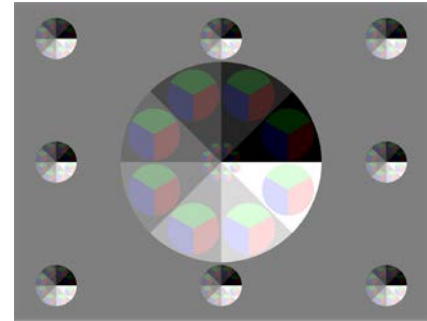


FIGURE 4.4. Pattern for color and grayscale inversion.



FIGURE 4.5. Patterns for adjustment of the near-white and near-black gray levels.



4.11. Moving-Picture Resolution, Visual Assessment

ALIAS

Visual resolution for moving sine bursts, visual assessment of dynamic limiting resolution.

DESCRIPTION

Determine the visual resolution by visually examining a set of four-cycled sinusoidal burst patterns having steps of spatial frequencies scrolled on the sample display. The visual resolution shall be the maximum spatial frequency up to which the four individual black lines are distinguishable.

Disabling over-scan, or “dot by dot” setting is required (this means that the display setting of the screen size or aspect ratio is 1:1 with the signal input so that any over scan is disabled; for example, the entire screen of HDTV is showing at a 1920×1080 pixel count, no pixels are missing because of over scanning). The test chart should contain sinusoidal bursts of four-cycle duration with steps of resolutions and should have different amplitudes and different backgrounds as shown in FIGURE 4.7 and FIGURE 4.8. Markers should be labeled to indicate each spatial frequency in the test chart as shown in Fig. 3. To secure stable results, the signal generator requires a sub-sampling functionality, which is realized by outputting the contents of two frame buffers alternately and shifting the pixel position in every two frames. (The pattern for 1920×1080 pixel count is supplied with the printed version of this document [4.1].)

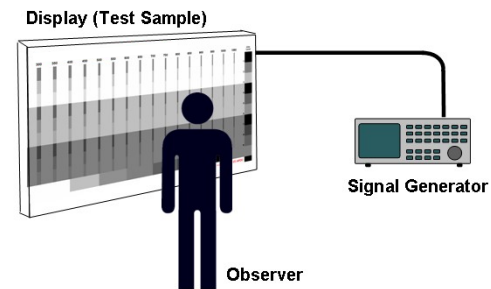


FIGURE 4.6. Moving picture resolution, visual assessment

PROCEDURE

Place yourself at a comfortable viewing distance from the screen that permits you to see the pattern distinctly, we suggest between 30 cm and H (the screen height).

1. Scroll the test chart as shown in FIGURE 4.7, with an appropriate scrolling speed. We used to use 6.5 pixels per frame (PPF, ~5 sec/screen) as a typical speed. However, that may be too slow, and a faster speed like 8 PPF, 8.5 PPF or even faster should be better.
2. Examine the maximum resolving spatial frequency for each band, consisting of a set of sinusoidal bursts with the same amplitude and the same background as shown in FIGURE 4.8. Observation shall always be made from lower to higher spatial frequencies in each band.
3. Repeat the above procedure for the different scrolling speeds.

ANALYSIS

To avoid misjudgment induced by possible false resolution, observation shall always be conducted from lower to higher spatial frequencies. For an effective and reliable visual assessment, it is suggested that the step width is 5 % of the number of pixels in the full screen height, for example, 50 lines of resolution for 1080i/p format.

REPORTING

Report visual resolutions for each band and calculate the average for all bands as shown in TABLE 4.1. Report the averaged resolution for each observer and calculate the average for each scrolling speed as TABLE 4.2 to plot FIGURE 4.9.



COMMENTS

See figures next page (“subject” in the table means a person). A more quantitative rendering of this method is found in the Motion-Artifacts Chapter (12), 12.2.1. Regarding observation distance, the idea is to make a yes-or-no answer such as whether or not there are four lines. A viewing distance of three screen heights ($3H$) is too far.

REFERENCE

4.1 Kawahara, I. (2009), P-189L: Late-News Poster: Advantages of Sinusoidal-Burst Based Measurement of Moving Image Performance. SID Symposium Digest of Technical Papers, 40: 1389-1392. <https://doi.org/10.1889/1.3256562>

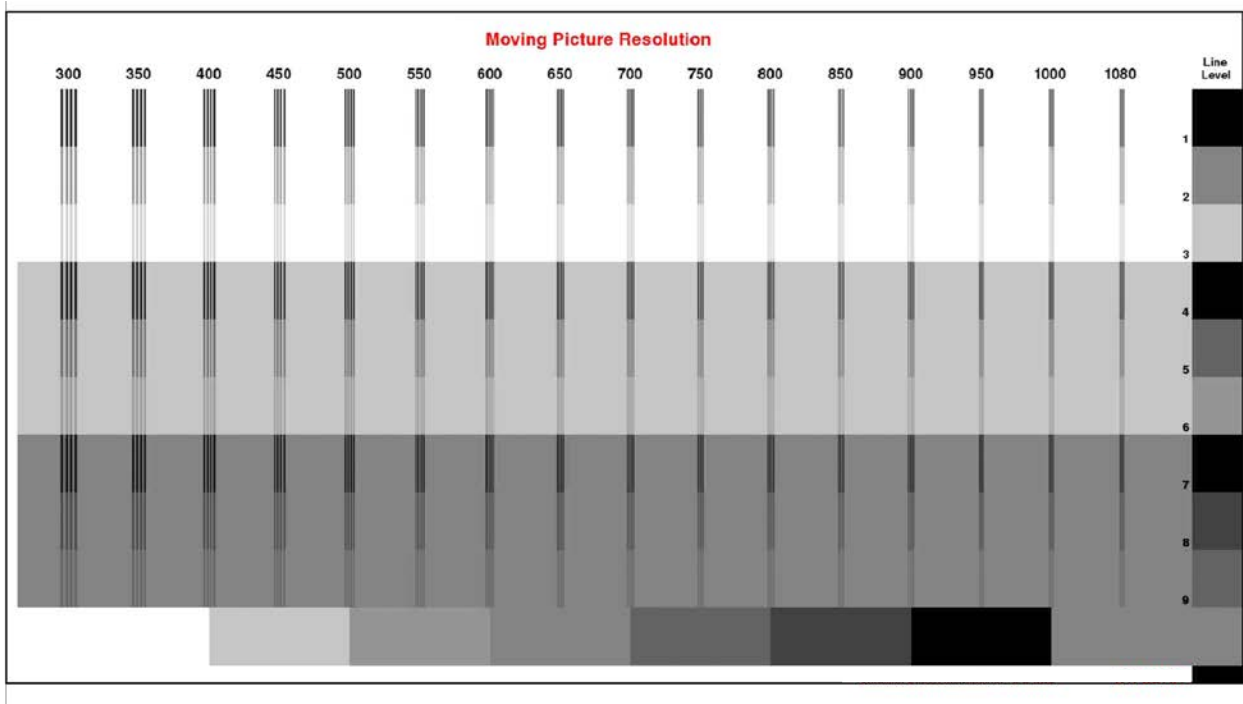


FIGURE 4.7. Test Chart.

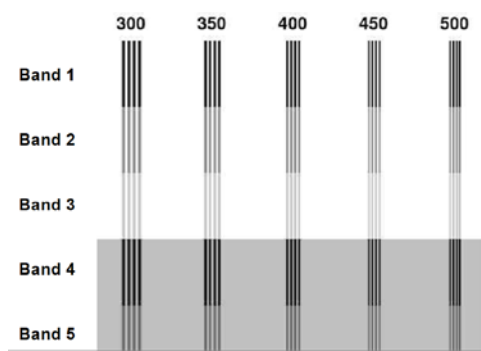


FIGURE 4.8. Close-up of FIGURE 4.7.

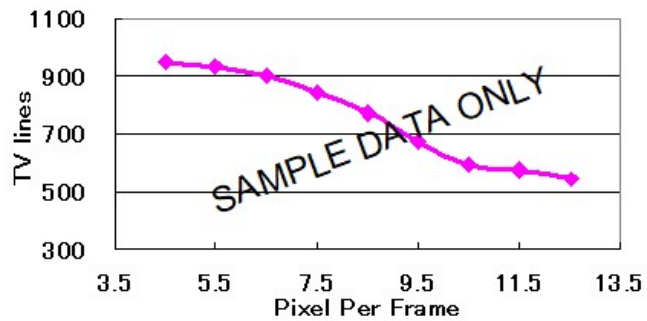


FIGURE 4.9. Visual assessment of resolution.



TABLE 4.1. Number of visually resolved line pairs at a scroll speed of 6.5 PPF.

Sample data only: Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Band	1	2	3	4	5	6	7	8	9	Avg.
Subject 1	800	950	1000	800	850	900	950	1000	900	906
Subject 2	750	950	950	800	800	900	900	950	900	878
Subject 3	850	950	900	850	900	900	950	950	1000	917

TABLE 4.2. Number of visually resolved line pairs at various scroll speeds (PPF).

Sample data only: Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Speed	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
Subject 1	950	950	905	850	772	677	600	572	544
Subject 2	900	900	877	833	750	650	577	550	544
Subject 3	1000	950	916	850	800	700	600	600	544
Average	950	933	899	844	774	676	592	574	544

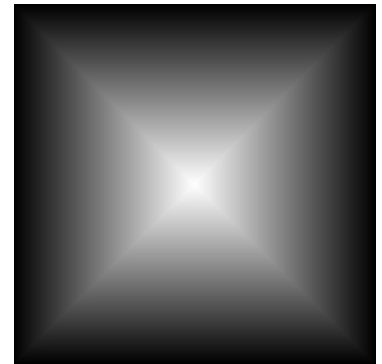
4.12. Gamma and Gray-Scale Distortions

ALIAS

drive-level assessment, gamma-curve gray-pattern distortion

DESCRIPTION

Using the ICDM fixed pattern of a sectioned, 256-level linear gradient from black to white (shown to the right), perform a visual assessment to help determine if a display operates properly when driven correctly, to verify it is operating in a linear range or being driven into distortion.



The range of operation for a display can be defined by its gamma curve, or the electro-optical transfer characteristics of the display, how linearly the luminance output is displayed for the drive input. By using the linear range pattern shown or an inverse version of it, we can make several observations to help indicate a display is operating non-linearly and help determine if display setting are not set up properly. This is not a substitute for making actual gamma curve measurements, but rather is a simple visual aid to help determine if some setup condition is not adjusted properly. By visual observations, we can make some determination about the gamma curve response of the display.

The pattern shown should appear as a continuous blend of black on the edges toward white in the center. If we see variations where the blend is distorted, then it may indicate misadjustments with the adjustment controls of the display. Dark room conditions are preferred, but this assessment can be done in ambient illumination, if necessary. Set up the quad-sectioned, linear gradient for visual observation. The 225-level version is preferred so that all levels are included—see appendix A12 Images and Patterns for Procedures; this pattern CJKW256 is available at DOI:10.55410/lgam8989.

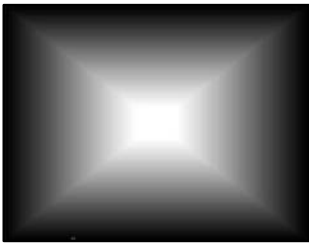


FIGURE 4.10. White clipping: excessively bright area but may become full white suddenly.

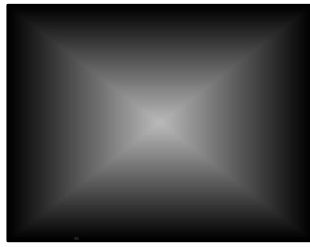


FIGURE 4.11. Underdriven: low gain offset, the overall pattern luminance level is low.

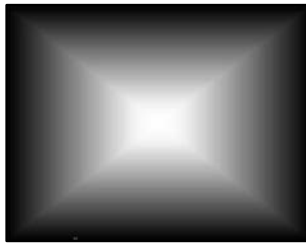


FIGURE 4.12. White level compression: excessively bright area.

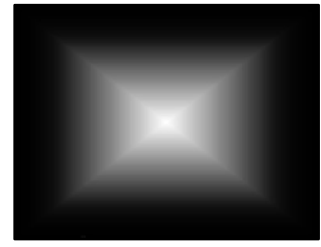


FIGURE 4.13. Black level compression: black region is too dark.

ANALYSIS

Look for variations of the pattern where the black levels around the edges appear or white center may appear degraded. Here are some examples of what to look for. There are many other possibilities not covered here. Here are some areas to investigate if non-linear anomalies are observed.

- The display setup might have a setting like “contrast,” “gain,” “offset,” or other terminology which indicate that the display drive level is set up optimally. These can also be part of factory setup conditions or hidden adjustments that might be in special OSD (on-screen display) menus or board interfaces not generally accessible. Gamma curve distortions such as those shown here could result from improper adjustments.
- Other conditions can also cause these types of distortions. It is impossible to account for all items which might produce distortions in performance. We can only suggest a few areas to explore.
- A gray-scale measurement (gamma curve) will be a more accurate indicator if any of these conditions exist and is recommended if more details of the gray linear response are desired.

COMMENTS

Assure that the source is driving the display correctly and not causing non-linear driving conditions which could be seen with the same visual anomalies. The exaggeration of the bright area of the center of the pattern as shown in FIGURE 4.10 can be caused by a number of characteristics of the display. It may be caused by high drive levels which produce more output for a given level at the input. For some display types of displays with viewing angle sensitivities, such visual artifacts can be seen by viewing the display off-axis, so it is very important to view the display at the normal, or perpendicular direction. Sometimes distortions like these can occur which could cause these

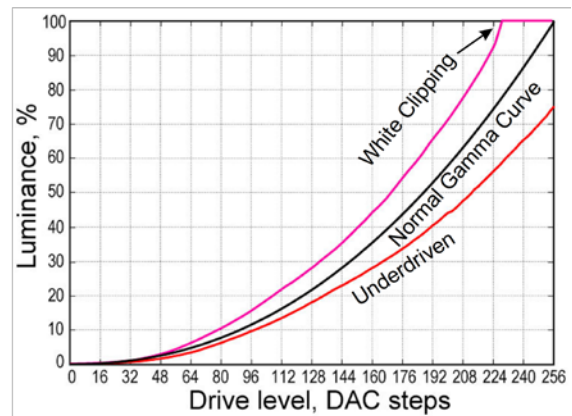


FIGURE 4.14. Gamma curves which show white clipping and being underdriven.

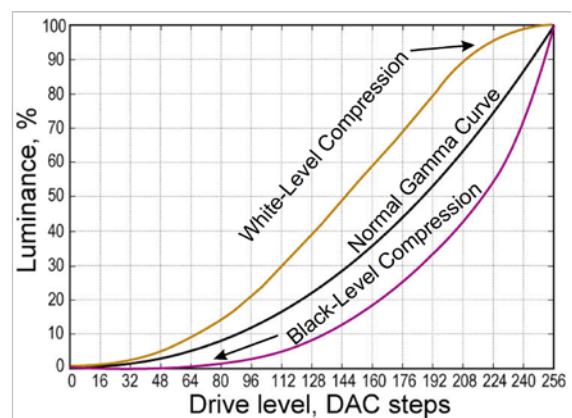


FIGURE 4.15. Gamma curves which show white and black level compression.



types of visual artifacts from other means, such as gamma driving compensation in video sources. Imbalances in color drive levels might also be seen by use of this pattern. Here are two examples:

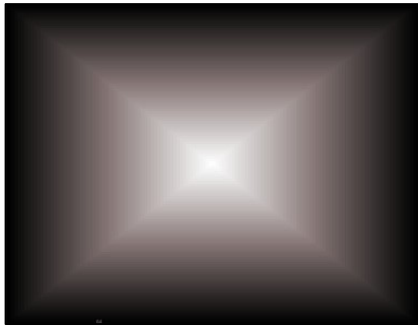


FIGURE 4.16. Color imbalance showing a high red drive.

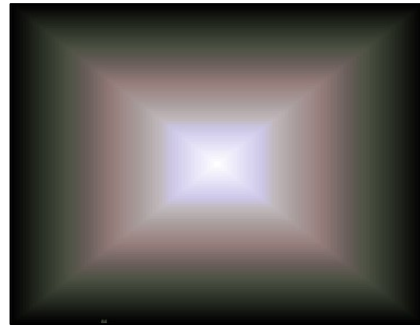
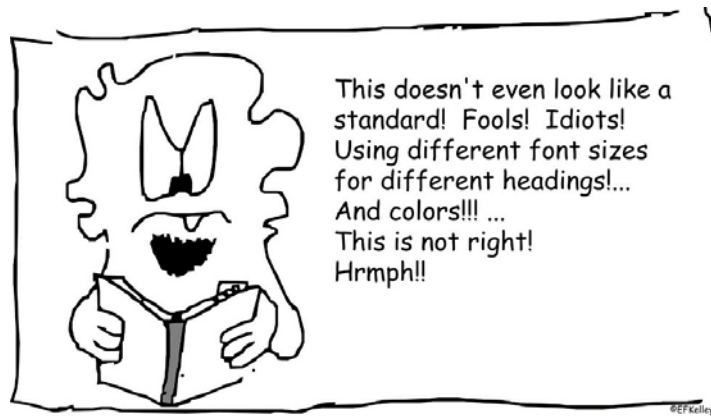


FIGURE 4.17. Color imbalance showing red, green, and blue intra-gamma band drive anomalies. For this figure, green is overdriven near the black region, red is overdriven in the mid-range, and blue is overdriven in the region near white.

Alternate patterns which can be used to observe for display non-linearities due to it being driven improperly.



4.13. Briggs Roam Test

DESCRIPTION

Quantify the visual resolution as a function of motion speed using a Briggs Roam checkerboard test pattern. The Briggs roam test pattern is comprised of rows of repeating Briggs checkerboards. The difference between the commanded contrast between the light and the dark checkers is typically 1, 3, 7, or 15. The surround is specified by the average checker level (for 0 and 255 command levels) as $S = 127.5 + 0.7(A - 127.5)$, where A is the average checker command level [4.2]. The test pattern is set in motion using an appropriate image viewer application that does not apply enhancements (nondestructive) to the image such as Motion Artifact Pattern Generator (MAPG) included at DOI:[10.55410/depi8030](https://doi.org/10.55410/depi8030) to display test patterns for subjective evaluation and measurement of moving pattern artifacts. The Briggs raw scores are visually determined and converted to

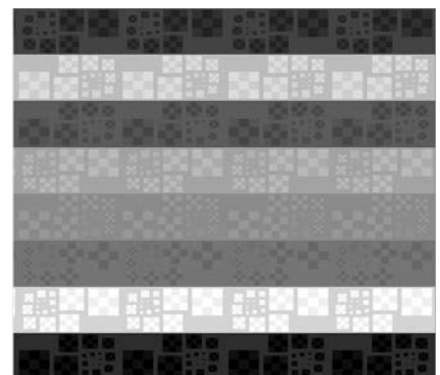


FIGURE 4.18. Sample of Briggs Grayscale Roam test pattern.



percent of total number of addressable pixels. Roam speed is converted to units of degrees of visual angle per second to facilitate comparisons of displays regardless of their pixel spacings.

Units: Degrees per second. **Symbol:** °/s.

SETUP

As defined by these icons, standard setup details apply (3.2).



In order to achieve optimum results, be sure to utilize the native addressability of matrix-addressed displays such as LCDs. Optimize the image viewer application configuration, e.g., magnification set to $1 \times$ (100%), and graphics card driver settings, e.g., OpenGL or DirectDraw.

PROCEDURE

1. Install and launch image viewer application that can display the Briggs test pattern in motion.
2. Configure the viewer to provide an accurate test pattern presentation, *i.e.*, no enhancements applied.
3. View the Briggs roam test pattern.
4. Visually identify the smallest checkerboard within each stationary (static) Briggs target panel that can be seen clearly enough to count all the light and dark checkers - the checkers may be fuzzy as long as you can count how many there are. Record the appropriate Briggs raw scores according to the scoring key.
5. Enable the viewer to set the test pattern in motion. Determine the motion speed (pixels/second) by measuring the distance (in pixels) and time (in seconds with stopwatch) as the edge of the Briggs test pattern travels once across the display screen.
6. Obtain visual Briggs scores at each roam speed. While the targets are moving, record the smallest resolvable Briggs checkerboard in each row. Ideally, there should be no difference between the static and moving scores.

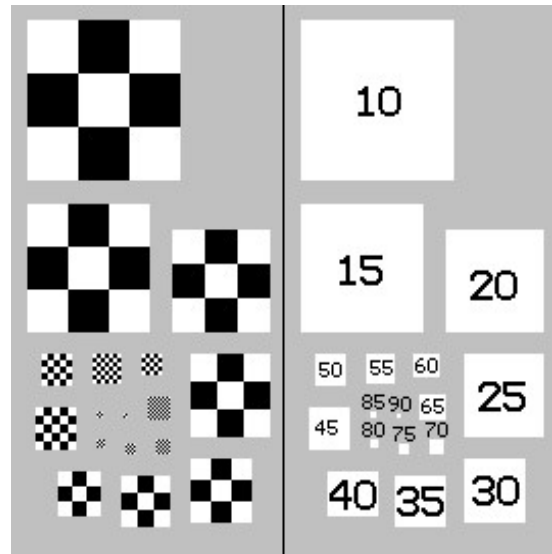


FIGURE 4.19. Briggs target and raw-score.

ANALYSIS

Use the measured viewing distance (typically 46 cm) and pixel spacing to compute the visual angle subtended by a single pixel, then calculate the roam speeds as they relate to distance traversed within the observer's visual field (degrees per second) by multiplying the number of degrees of visual angle subtended by a single pixel by the roam speed in pixels per second. The raw (unadjusted) Briggs scores convert directly to percentages of total resolution as listed in the table, provided the display is operated at the native addressability and the image viewer is set for $1 \times$ magnification.

REPORTING

Report the fastest acceptable roam and rotation speeds in degrees of visual angle per second for which no loss in Briggs scores occur - use the static image score as a reference.

COMMENTS

it is recommended that a variety of Briggs panels are evaluated so that motion blur is sampled over the entire range of gray levels. The worst case and average scores are typically reported. A bias value of 2 (8 if base score is 90) can be added to the base score of a checkerboard if its edge detail is especially well-defined. Briggs targets are scored



visually, so there can be large differences between users. Training of the evaluator should be given to assure satisfactory repeatability of scoring and to achieve agreement with other evaluators. According to the Briggs reference cited, on page 398 section 2.3 states that to get the best image to the retina, the observer can be as close as 4 inches or as far as 10 feet away and may use his/her glasses with bifocals and other aids provided they help. Optical aids are allowable and viewing distances as close as 4 inches may be desirable, however, observers should employ optical aids only when necessary, and such aids must only compensate for refractive errors, without adversely increasing magnification. Excessive magnification may influence results, especially when assessing high spatial frequency content. The precision of this measurement could be improved by performing some sort of pursuit-camera-like contrast modulation measurement of the target, rather than a visual score. Evaluating a monitor using its native luminance response makes it difficult to compare measurements of different monitors. Therefore, utilization of the equal probability of detection (EPD) luminance response (see the Metrology Appendix A12.5 Visual Equal Probability of Detection Target) calibration is recommended in order to provide more visually discernable gray levels - a NEMA-DICOM calibration would produce similar results; however, there is less separation within the “dark” region (see the Tutorial Appendix B25 NEMA-DICOM Gray Scale).

This procedure has been used successfully for evaluation of the roam speed of a desktop or larger monitor having CRT, LCD, OLED, or plasma technology. This procedure may not be practicable for assessing high speed motion on very small displays because the human vision system requires sufficient dwell time to perceive the moving Briggs target as it traverses the screen. The Briggs panel is a target that is 256×128 pixels and has 17 checkerboard targets within it as shown on the left side of the figure. This Briggs target in the figure has been enhanced to show the pattern of the checkerboards from the largest to the smallest. Actual targets may vary in contrast and may not include this highest-contrast target. Each checkerboard pattern is assigned a numeric value that increases as the frequency of the checker pattern increases and as the size of the checkerboard decreases. These numeric values are the scores that are assigned to a target and display system when the chosen checkerboard is said to be completely visible. “Completely visible” is described as the state where it is possible to count all of the checkers in a checkerboard. To accurately score the Briggs target, follow the rule of thumb, which dictates that the checkers in the checkerboard must be countable. Experience in scoring also increases confidence in this determination.

TABLE 4.3. Analysis Example: Briggs Target Resolutions
Sample data only: Do not use any values shown to represent expected results of your measurements.

Number of Pixels per Checker	Number of Checkers per Target	Briggs Target	Number of Pixels per Checker
25×25	3×3	10	4%
20×20	3×3	15	5%
16×16	3×3	20	6%
13×13	3×3	25	8%
10×10	3×3	30	10%
8×8	3×3	35	13%
7×7	3×3	40	14%
4×4	5×5	45	25%
3×3	5×5	50	33%
2×2	7×7	55	50%
2×2	5×5	60	50%
1	11×11	65	100%
1	7×7	70	100%
1	5×5	75	100%
1	4×4	80	100%
1	3×3	85	100%
1	2×2	90	100%

REFERENCE

- 4.2 S. James Briggs, David Heagy, Ronald Holmes, “Ten-year update: digital test target for display evaluation”, Proc. SPIE 1341, Infrared Technology XVI, (1 November 1990); <https://doi.org/10.1117/12.23113>



TABLE 4.4. Reporting Example

Sample data only: Do not use any values shown to represent expected results of your measurements.

Pixel spacing	0.254 mm	Maximum Roam Rate	
Viewing distance	457.2 mm		
Briggs Score	Resolution (%)	Pixels per second	Degrees per second
90	100	0 (Static)	0 (Static)
90	100	60	1.910
60	50	180	5.730
50	33	300	9.549



5. Fundamental Measurements

These are the most straightforward measurements of the luminance (or spectral radiance), the color, and the correlated color temperature (CCT) of various simple patterns either at the center or in the vicinity of center.

5.1 Black and White Characterization Issues

Modern displays have created some interesting measurement problems. In particular measurements of both white and black can have issues that we outline here.

FULL-SCREEN WHITE

Some displays may employ features or processing to increase or decrease the luminance of white relative to the levels expected from the additivity of the standard set of RGB input signals. The effects of these features or processing are included in 5.3 *Full-Screen White* measurement. Enhanced white levels may be useful in showing text and providing highlights to certain images or to create artistic results in the images; however, such enhanced white levels may not be desired when displaying imagery when it distorts the grayscale or gamut volume so that the saturated colors appear relatively darkened. To provide a measurement of the white used for imagery, we have the measurement *Color-Signal White* in 5.4. The full-screen white luminance must be reported as “full-screen white luminance” to avoid confusion with other white measurements such as peak white.

PEAK WHITE OR HIGHLIGHT WHITE

Some display technologies display a full-white screen with less luminance so that they would show a small white box on a black screen. This has to do with screen Loading (see 5.24). Such a performance can be regarded as an advantage and may be documented. We have provided a measurement to characterize the White Box on Black 5.25.1 and the Peak White or highlight luminance (5.5) to provide a means to favorably characterize such displays. However, if the highlight or box luminance and contrast is reported it must be labeled “box” or “highlight” luminance or contrast just as the full-screen white luminance must be also reported as “full-screen white luminance.” This way, the impression is not left with the user that the full-screen white is at the level of the highlight white whenever they differ.

BLACK

1. **Full-Screen Black:** For those displays that exhibit a non-zero luminance for a full-screen black pattern, we provide the Full-Screen Black measurement in 5.6. However, some displays are able to create a zero-luminance black, especially for full-screen black. Current technologies that can do this are able to completely turn off the pixel (as with some LED or OLED displays). Some displays have global dimming or local dimming capabilities (as with LED backlights for LCD displays) where the LEDs in the backlight can be turned off. In some cases, true zero-luminance values are obtained in regions of the display where the image is commanded to be black; thus, providing for an infinite contrast ratio compared to white no matter what that white value may be.
2. **The Intention:** The full-screen black measurement often serves in determining the full-screen or sequential contrast of a display. The intention is that whenever images are displayed, no matter how extremely dim or isolated in one region of the screen, we want to use a black level that is associated with the display of images. However, it is not always true that full-screen black is representative of a black found in even dark images; so we have to look at cases.
3. **Observing Luminance of Black:** Note that if you find that it is difficult to see any light from a black screen and you are using a quality darkroom, allow your eyes to become dark adapted (see Dark-Adapted Eyes below), and then see if you can observe any light from a black full screen. Some are helped to see any light from the black screen by obtaining a black flat mask with a 25 mm to 50 mm hole in its center and placing the mask at the center of the screen (perhaps without touching the screen if the screen's luminance is sensitive to mechanical pressure). If you can see the hole as being lighter than the black mask with dark-adapted eyes, then there is a



low-level black luminance present—of course, this requires a quality darkroom with no stray light on the mask (see Dark-Adapted Eyes below). Only if no luminance can be observed with dark-adapted eyes can a zero-luminance black be reported using these methods.

4. **Measuring Low-Level-Luminance Black:** Some display technologies create blacks with luminances so low that they cannot be measured by the instrumentation employed. Nevertheless, the eye can see some luminance in the center of the black screen. In such a case, we need to employ a more sensitive instrument rather than reporting a low or zero-luminance black. Additionally, the instrument we use must have sufficient sensitivity and precision to give an accurate ($\pm 4\%$) black measurement to at least two significant figures. Discussions of how to establish low-light-level measurement accuracy are provided in the Metrology Appendix A3 Low-Light Measurements.
5. **Zero-Luminance Black:** Some display technologies can, indeed, create a black full screen that exhibits no luminance. However, such blackness may be misleading if any dim image that is placed on the screen changes the central black so that it has a finite luminance—even when such dim images are placed in a corner and away from the center measurement region. We have included a measurement method in 5.7 Image-Signal Black and 5.13 Corner-Box Contrast in order to provide a means of testing whether or not a low- or zero-luminance black can be reported for the purpose of image display. If the image-signal black measurement method yields an observable non-zero luminance L_{KCS} , then that color-signal-black luminance L_{KCS} may be considered in determining contrasts used for imaging purposes rather than full-screen black.
6. **Full-Screen Black, Sequential Black, or Scene-Transition Black:** There are technologies that can create a zero-luminance black level when showing a full-screen black, but as soon as anything appears on the screen, even something very dim and isolated off in the corner, the black level at center-screen changes to a visible luminance. For such a display, a full-screen black measurement is not a useful representation of how imagery will be shown; that is, it is not useful to represent black for imagery. However, such a black screen may be useful for transitions between scenes, and therefore be of interest.
7. **Infinite Contrasts vs. Undefined Contrasts:** Reporting an infinite contrast is not very useful in itself and will not be permitted in this document. It only tells you that you have a zero-luminance black. When such is the case, no matter what the white luminance is, the contrast, as defined by $L_W L_K^{-1}$, remains infinite or undefined for any nonzero white luminance. To avoid the problem of infinite contrasts we might be tempted to employ a limiting black luminance, but until more research is done on this matter, we will simply refer to contrasts based upon a zero-luminance black as “undefined.” In such cases it is best to separately report the white luminance (whichever white is employed) and report the black luminance as zero or unmeasurable.

DARK-ADAPTED EYE

In a good darkroom, it will take up to 45 min or more for the eyes to become dark adapted. Looking at a bright light or a computer screen will destroy that dark adaptation. To be able to judge a screen as having an absolute black level of nearly zero will require dark-adapted eyes or an instrument that is capable of accurately measuring luminance levels in that range with any non-black area masked off. NOTE: When we are using our dark-adapted eyes and when we are in a good darkroom not looking at instrument lights or display screens, we are not using photopic vision, and we are therefore not really seeing luminances. However, because much of the equipment measures photopic quantities, for the purposes of this standard, we will accept low-light measurements from photopic instrumentation and use luminance. Keep in mind that under most display operations where brighter information is being displayed, the eye is in a photopic mode after all.



VEILING-GLARE CONTRIBUTION

The use of a mask, especially a glossy black frustum mask, can provide more accurate measurement results because of eliminating veiling glare in the detector even when viewing a white screen or large areas of grays or colors—see Appendix A2 Stray-Light Management. In FIGURE 5.1 we show a gloss black frustum (cone with tip cut off) at the end of a matte-black tube for making luminance measurements using a detector with a focusing lens. We will call this a frustum-tube mask, which is one version of a stray-light-elimination tube (SLET). The tip of the frustum is placed as close to the screen as is feasible without touching the screen. Such a mask is particularly important when measuring a box of a dark color with brighter surroundings. Please be sure to review Appendix A2 Stray-Light Management.

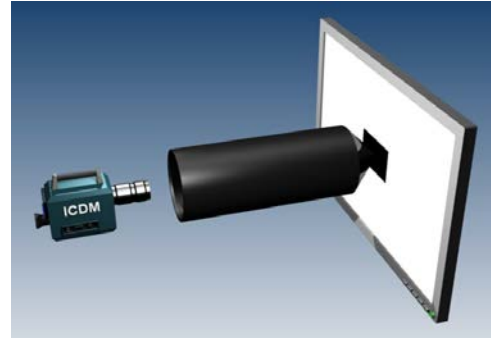


FIGURE 5.1. Frustum-tube mask for a detector with a lens—one version of a stray-light-elimination

5.2 Measurement Repeatability

DESCRIPTION

We measure the repeatability of, for example, a luminance measurement. We obtain an estimate of the mean and standard deviation of a luminance measurement by making 10 measurements of the luminance of a source.

Units: cd m^{-2} for mean and standard deviation.

Symbols: μ_L and σ_L respectively.

SETUP

As defined by these icons, standard setup details apply (3.2).



If you use a display, use a full-screen white pattern (e.g., FW*.PNG) with a DUT that has warmed up for over one hour. Preferably, use a stable laboratory light source. Be sure that the luminance meter and the source of light are securely in place and will not change in their positions during the measurements. A stable laboratory light source is suggested so that concern over drifting of the DUT is eliminated.

PROCEDURE

Measure the luminance of the source 10 times as quickly as is reasonably possible.

Graph the luminance as function of the measurement order number, one through ten (which provides an approximation to the luminance as a function of time).

ANALYSIS

Calculate the mean and standard deviation for the luminance measurements and examine the graph of the results to see if there is any drift due to inadequate warm-up of either the source or the LMD. The mean μ_L of $n = 10$ measurements of the luminance L_i is

$$\mu_L = \frac{1}{n} \sum_{i=1}^n L_i \quad (5.1)$$

and the standard deviation is

TABLE 5.1. Luminance μ and σ of a DUT

Sample data only: Values shown here are for illustration purposes only; they do not suggest expected measurement results.

L_1	102.7
L_2	102.5
L_3	103.1
L_4	102.3
L_5	102.8
L_6	103.1
L_7	102.6
L_8	103.1
L_9	103.5
L_{10}	103.4
μ_L	102.9
σ_L	0.393



$$\sigma_L = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (L_i - \mu_L)^2} \quad (5.2)$$

If there is an overall drift in the values which results in the primary contribution to the standard deviation, then it may be wise to wait until warm up is achieved and attempt a re-measurement. The standard deviation is a measure of the short-term repeatability of the source and LMD.

REPORTING

None, unless called for by the interested parties. Some may wish to report the mean and standard deviation of these ten measurements in the comments if the reporting document permits.

ADDITIONAL COMMENTS

The light-measurement device (LMD), the light source or display under test (DUT), or both in concert can cause non-repeatability. Most measurements made using this document depend upon the repeatability of a measurement result being relatively small; in which case only one measurement is generally needed—see A5 Adequacy of Single Measurements. In the graph above of the sample data we see an upward drift in the luminance (the line is a linear fit to the data) However, the upward drift is disturbing, and if continued over a long time can substantially compromise the accuracy of the measurement results. If such drifts (upward or downward) are observed, it may be wise to sample the measurements over a longer time period and wait until we can assure stability of the source and LMD before proceeding further. This measurement can be used in conjunction with A3 Spatial Invariance and Integration Times. Using a stable laboratory source can exhibit drifts on the order of 0.1 % per hour and will help diagnose detector (LMD) drift.

Note: Although we have specified a luminance measurement in this example, any measurement result can be dealt with in a similar fashion, e.g., chromaticity coordinates, illuminance, spectral radiance, CCT, as well as other measurement results.

5.3 Full-Screen White

ALIAS

Brightness³, white screen, screen brightness³, display luminance, white-screen luminance

DESCRIPTION

We measure the center luminance and optionally the chromaticity coordinates and CCT of full-screen white. **Units:** cd m⁻² for luminance, no units for chromaticity coordinates, K (kelvin) for CCT. **Symbol:** L_W for luminance, x, y for the 1931 CIE chromaticity coordinates, T_C for CCT. Here L_W is created by supplying the display with the maximum signal for the R, G and B inputs simultaneously.

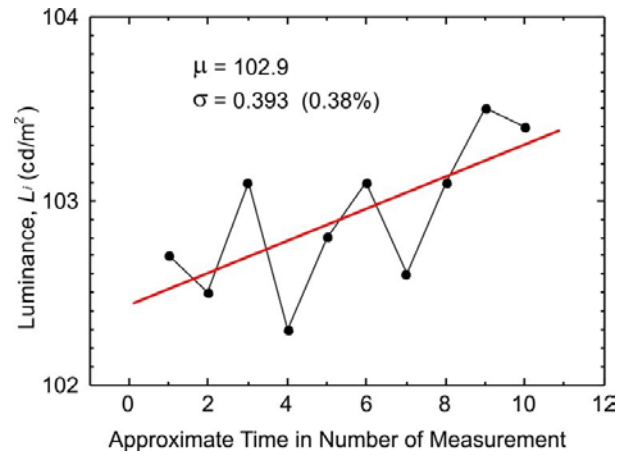


FIGURE 5.2. Sample data only: Do not use any values shown to represent expected results of your measurements.

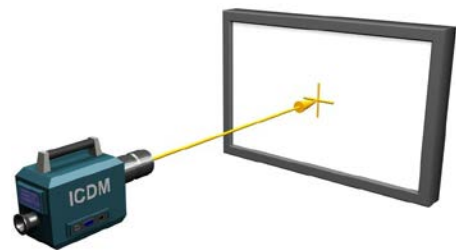


FIGURE 5.3. LMD geometry for full-screen white measurement

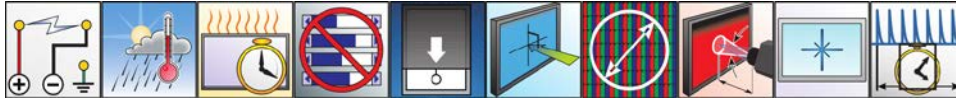


APPLICATION

Emissive displays: In general, this method is not suitable for front-projector displays except with modifications. For reflective displays, careful attention needs to be given to the ambient illumination environment.

SETUP

As defined by these icons, standard setup details apply (3.2).



Full-screen white pattern, *e.g.*, FW* . PNG.

PROCEDURE

Measure and record the luminance, etc., as many significant figures as available from the detector.

ANALYSIS

None.

REPORTING

Report the luminance, chromaticity coordinates, and CCT as needed. Unless more precision is warranted, limit the luminance to three significant figures (or less, particularly for small luminance values), the chromaticity coordinates to four (or less), and the CCT to three.

TABLE 5.2. Reporting example: Full-Screen White.
Sample data only: Do not use any values shown to represent expected results of your measurements.

White	$L(\text{cd m}^{-2})$	CCT (K)	x	y
	L_W 193	6070	0.3195	0.3544

COMMENTS

1. Stray Light: For making the most accurate measurements of luminance, the use of a frustum tube is advisable in order to eliminate stray light and veiling glare from the bright areas outside the measurement field.
2. Display Modes: Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see 2.1 Display Description, Identification, and Modes and 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.
3. The term “brightness” is a qualitative term whereas “luminance” is a quantitative term. Avoid using “brightness” for “luminance” as it should never be used as a replacement for “luminance”—see the appendix E. Glossary and B1. Light and Radiation Measurements. Also, you may give the appearance of ignorance if you use “brightness” except in a qualitative sense. For example, we might say, “Please turn up the brightness of that display.” But we would be embarrassingly wrong and appear ignorant if we said, “The brightness of the display is 250 cd m^{-2} .” Brightness is the attribute of a visual sensation to which an area appears to emit more or less light, and the term is receiving a quantitative definition in the CIECAM02 color appearance model under development as of this writing. See 5.30 Perceptual-Contrast Length for a quantitative discussion of “brightness.”

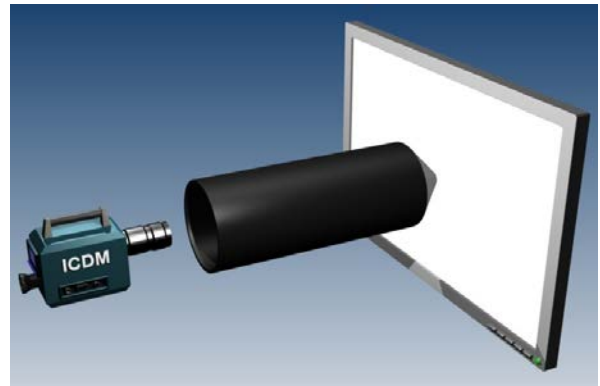


FIGURE 5.4. Stray light elimination tube (SLET).



5.4 Color-Signal White

DESCRIPTION

We measure the center luminances of three patterns (nonatile tri-sequence patterns) and add those luminances to give the luminance of color-signal white. *Note the application immediately below.* **Units:** cd m^{-2} for luminance. **Symbol:** L_{CSW} . (Optionally, it may be useful to also record the chromaticities of the center colors.)

APPLICATION

For color displays in which the input signals conform to a standard set of RGB voltages or digital values, this method is used to determine and to report if the luminance of white L_{W} (such as 5.3 Full-Screen White above) approximately equals the combined luminances of the individual R,G and B primaries, where the RGB colors are created by supplying the display with the maximum signal for each of the R , G and B inputs independently. This test verifies additivity of the color signal primaries. If it is the case that

$$L_{\text{W}} \neq L_{\text{R}} + L_{\text{G}} + L_{\text{B}} \quad (5.3)$$

then such a display may exhibit characteristics, employ features, or provide processing to increase or decrease the luminance for portions of the display color gamut. These displays may produce nontrivial errors in colorimetric reproduction and color appearance from the intention based upon the color signal. If the relationship of the input signal primaries to signal white is properly maintained, as in

$$L_{\text{W}} \cong L_{\text{R}} + L_{\text{G}} + L_{\text{B}} \quad (5.4)$$

then any colorimetric or color-appearance errors due to non-additivity should be minimized. This equation may not hold precisely for systems with nontrivial anomalies such as a lack of color-channel independence and power supply limitations.

SETUP

As defined by these icons, standard setup details apply (3.2).



Use the nonatile tri-sequence patterns, *e.g.*, NTSR*.PNG, NTSG*.PNG, NTSB*.PNG, and measure the center box in each pattern.

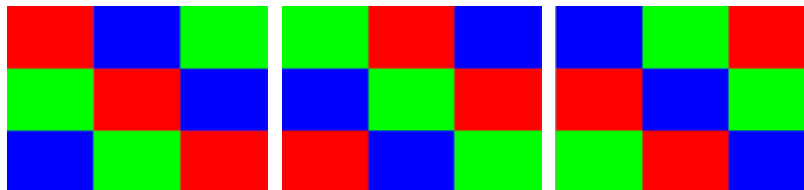


FIGURE 5.6. Nonatile-trisequence patterns (NTSR, NTSG, NTSB, respectively). The RGB rectangles are fully saturated RGB colors at maximum luminance.

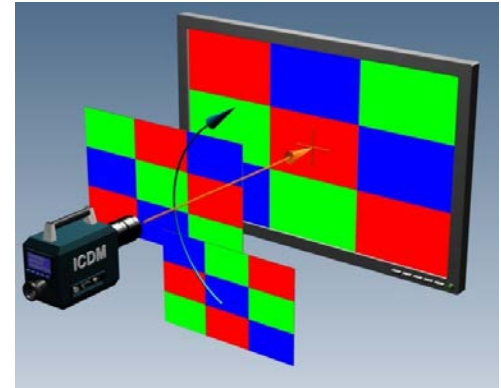


FIGURE 5.5. Center luminance measurements of nonatile tri-sequence patterns.



ALTERNATIVE PATTERN

An alternative pattern may be used with any display, but it is especially for displays with loading characteristics: Multicolor Pattern with Constant 25% APL, see Metrology Appendix A12.6. The pattern maintains the pre-gamma average pixel level (APL) at 25 % independent of what center color is being measured. Each of the nine large boxes have 2/9 the width and height of the active display screen area. The only box that is measured is the center box. The small dark gray boxes in the outer eight boxes are the digital compliments of the larger center box. Thus, if the center box is white giving L_W then the small gray boxes will be black; if the center is red giving L_R then the small gray boxes must be cyan; if the center is green giving L_G , then the small gray boxes must be magenta; and if the center box is blue giving L_B , then the gray boxes must be yellow.

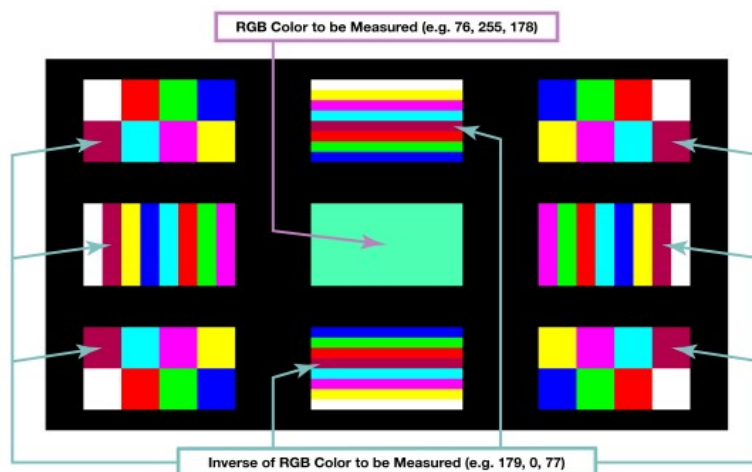


FIGURE 5.7. Center luminance measurements of 25% APL pattern (see Metrology Appendix A12.6).

PROCEDURE

Measure and record the luminances of the center rectangle of all three of the nonatile-tri-sequence patterns as shown in FIGURE 5.6. If using the 25% APL pattern in FIGURE 5.7, then measure the center luminances of R, G, B, and W. (Optionally, for some applications it may be useful to also record the chromaticities.)

ANALYSIS AND REPORTING

Calculate the color-signal white luminance

$$L_{CSW} = L_R + L_G + L_B \quad (5.5)$$

If the full screen white luminance is not approximately equal to color-signal white luminance, $L_W \not\approx L_{CSW}$, then report the color-signal white luminance L_{CSW} to three significant figures.

COMMENTS

1. **Lower-Contrast Displays:** Note that if the luminance of the black screen is nontrivial, then a more accurate measurement of the color-signal white is

$$L_{CSW} = L_R + L_G + L_B - 2L_K \quad (5.6)$$

where L_K is the luminance of the full-black screen. This second equation helps account for the extra measurement of black subpixels on the screen whenever the display sequential contrast is less than 100:1, for example.

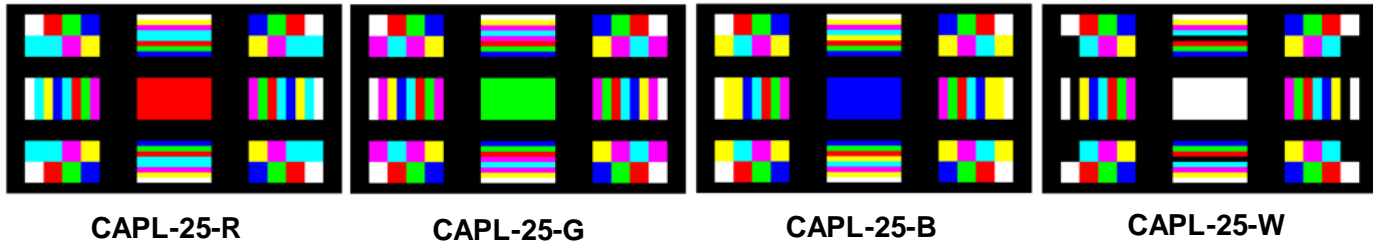
2. **Different Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see 2.1 Display Description, Identification, and Modes and 3.2.4 Controls Unchanged and Modes for details regarding mode settings and recording.



5.4.1 Color-Signal White Ratio

DESCRIPTION

We can avoid all loading problems by using the 25% APL pattern described in the previous section (see A12.6 in the Metrology Appendix).



Make center measurements of luminance (optionally chromaticity coordinates) using a frustum or stray-light elimination tube (SLET, see A2.1.1 and A2.1.5). Calculate the ratio of the white rectangle luminance L_{WCS} to the sum of the RGB primary colors

$$C_{CSW} = \frac{L_{WCS}}{L_{RCS} + L_{GCS} + L_{BCS}} \quad (5.7)$$

C_{CSW} may also be expressed as a percentage indicating the white boost over the white signal input.

5.4.2 Color-Signal White Including White and Black

DESCRIPTION

Measure the center luminances with the six patterns below. We don't generally use black in connection with CSW except for low contrast displays; see Eq. (5.6) above in 5.4. However, the white and black patterns do provide a measure of contrast for equal APL patterns:

$$C_{APL25\%} = \frac{L_W}{L_K} \quad (5.8)$$



5.5 Peak White

ALIAS

highlight luminance, peak luminance

DESCRIPTION

We measure the peak or highlight luminance of a small white 30 px (± 1 px) square at screen center. Optionally the chromaticity coordinates and CCT may also be measured. **Units:** cd m^{-2} . **Symbols:** L_p .

The size of the square is optional. If a larger square or rectangle will produce a brighter white, then it is permissible to use the larger area. The 30 px square is employed here to cover over the requisite 500 px to be measured under standard conditions in Setup.



SETUP

As defined by these icons, standard setup details apply (3.2).



Use a pattern with a 30 px square white box at center screen with a black background.

PROCEDURE

Measure the luminance of the box.

ANALYSIS

None

TABLE 5.3. Reporting Example: Peak White.

Sample data only: Do not use any values shown to represent expected results of your measurements.

L_P	257	cd m ⁻²
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REPORTING

Report the measured luminance L_P as “peak luminance” or “highlight luminance.” It is not permissible in this standard to use only the term “luminance” or “white luminance” in reporting peak luminance.

COMMENTS

For comparison purposes with other displays, it is important to keep the luminance of full-screen white and peak white as separate metrics. Thus, in any reporting documentation, it is not allowed in this standard to give the impression that peak white is full-screen white by leaving out the word “peak” or “highlight.”

5.5.1 Average Peak White

ALIAS

average highlight luminance, average peak luminance

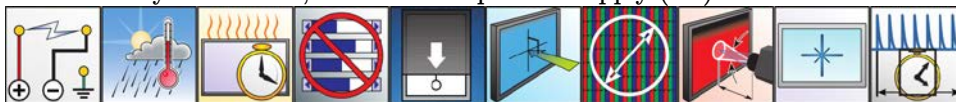
DESCRIPTION

We measure the average of the peak or highlight luminance of a small white 30 px (± 1 px) square at screen center and at least four other locations on the surface symmetrical about the center. Optionally the chromaticity coordinates and CCT may also be measured. **Units:** cd m⁻². **Symbols:** L_{Pave} .

The size of the square is optional. If a smaller square or rectangle will produce a brighter white, then it is permissible to use the smaller area. The 30 px square is employed here to cover over the suggested 500 px to be measured under standard conditions in the chapter on Setup. The boxes can be measured one at a time; they don't all have to be white at the same time.

SETUP

As defined by these icons, standard setup details apply (3.2).



Use a pattern with a 30 px square white box at five or more, $M \geq 5$, locations sampling the screen surface with a black background. One of the locations of the box must be center screen.

PROCEDURE

Measure the luminance of the box at five or more locations symmetrically sampling the screen surface. Be sure to include the center box. The boxes can be commanded to be white and measured one at a time; they do not all have to be white at the same time.



ANALYSIS

Calculate the average peak luminance from the measured peak luminances $L_n, n = 1, 2, \dots, M$ at the M locations:

$$L_{\text{Pave}} = \frac{1}{M} \sum_{n=1}^M L_n \quad (5.9)$$

REPORTING

Report the average luminance as “average peak luminance” or “average highlight luminance.” It is not permissible in this standard to use only the term “luminance” or “white luminance” in reporting a peak luminance.

TABLE 5.4. Reporting Example: Average Peak White.
Sample data only: Do not use any values shown to represent expected results of your measurements.

L_{Pave}	249	cd m^{-2}
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COMMENTS

For comparison purposes with other displays, it is important to keep the luminance of full-screen white and average peak white as separate metrics. Thus, in any reporting documentation, it is not allowed in this standard to give the impression that average peak white is full-screen white by leaving out the word “peak” or “highlight.”

5.6 Full-Screen Black

ALIAS

black screen, black-screen luminance

DESCRIPTION

We measure the center luminance and optionally the chromaticity coordinates and CCT of full-screen black. **Units:** cd m^{-2} for luminance, no units for chromaticity coordinates, K (kelvin) for CCT.

Symbol: L_K for luminance, x, y for the 1931 CIE chromaticity coordinates, T_C for CCT.

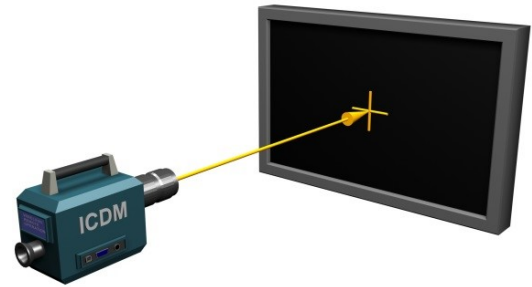
SETUP



As defined by these icons, standard setup details apply (3.2). Use a full-screen black pattern, *e.g.*, FK*.PNG. Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.

REPORTING

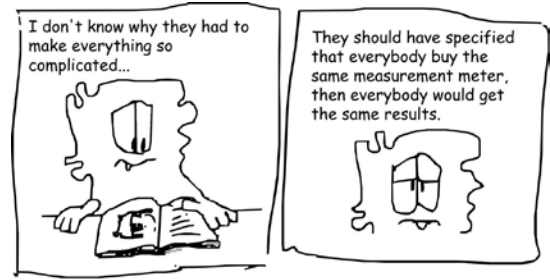
Before reporting a low luminance of 1 cd m^{-2} or less for this measurement, the measurement equipment must be able to measure the luminance with a 4 % or less relative uncertainty and provide at least two significant figures (see comments at the beginning of this chapter). If a dark-adapted normal eye in a good darkroom can see any luminance from the screen with or without a mask, then regardless of the capability of the LMD, a zero-luminance black must not be reported. If you can't measure it but can see it, then it has a luminance. This avoids the specsmanship of illegitimately reporting huge or infinite contrasts.





COMMENTS

(1) **Zero-Luminance Black:** If a zero-luminance black is obtained then infinite contrasts should not be reported for any metric that uses this black. Instead, report that the contrast as “undefined” and be sure that a white that characterizes the display is reported along with a zero-luminance black. Refer to 5.1 for more information regarding zero-luminance blacks. (2) **Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see 2.1 Display Description, Identification, and Modes and 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.



RUSTIC METROLOGY

TABLE 5.5. Reporting example: Full-Screen Black.

Sample data only: Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Test pattern	L_K (cd m ⁻²)	T_C (K)	CIE 1931 x	CIE 1931 y
Black	0.12	6070	0.3195	0.3544

5.7 Image-Signal Black

DESCRIPTION

We measure the luminance and optionally the chromaticity coordinates and CCT of the center black of pattern SCX32KX, which provides 32 (optionally 33) equally spaced levels of gray in concentric boxes from black to white distributed over the screen with a centered box 1/5 (or optionally 1/6) the linear size of the screen. **Units:** cd m⁻² for luminance, no units for chromaticity coordinates, K (Kelvin) for CCT. **Symbol:** L_{ISK} for luminance, x, y for the 1931 CIE chromaticity coordinates, T_{IS} for CCT.

The idea is to capture how the display renders black under imagery conditions where most of the display surface has non-zero luminance content.

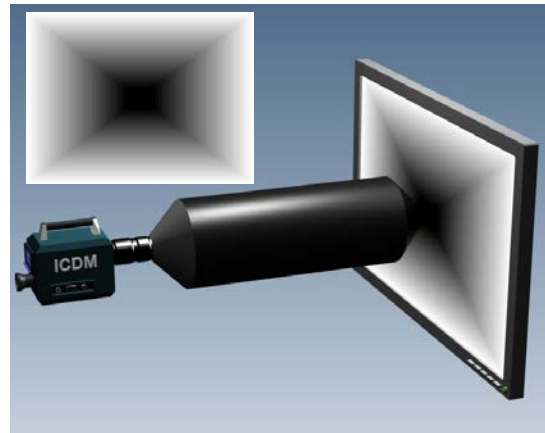


FIGURE 5.8. Measurement of image-signal black L_{ISK} using pattern SCXX32.

SETUP



As defined by these icons, standard setup details apply (3.2):

(1) **Pattern:** Use pattern SCX32KX, which is a 32 equal step (± 1) concentric-box gray scale filling the screen with a black center box that is $0.2 \times$ the linear size of the screen (see the Metrology Appendix A12). If another pattern is used, it must be agreed upon by all interested parties and reported with the measurement result. (2) **Mask:** A frustum mask (or a flat mask near or against the screen—possible heating of the screen with the flat mask can occur) is recommended to be used to eliminate veiling glare in the detector (see the Metrology Appendix A2 and Comments below).



PROCEDURE

1. Display pattern SCX32KX.
2. Install frustum mask (either large frustum or frustum with tube) so that no light reaches the lens of the LMD that comes from anywhere on the display (including the bezel) except from the central black region.
3. Measure luminance, etc.

REPORTING

Report the luminance L_{ISK} of image-signal black to no more than three significant figures. Optionally report the chromaticity coordinates and the CCT.

COMMENTS

(1) Patterns Used: If no qualifying statement is used to describe the pattern employed for this measurement, then the SCX32KX pattern must be used in the measurement. Other patterns have been suggested for use and may be used provided all interested parties agree and that the pattern used is reported in any reporting document. **(2) Zero-Luminance Black:** If a zero-luminance black is obtained then infinite contrasts should not be reported for any metric that uses this black. Instead, report that the contrast is “undefined” and be sure that a white that characterizes the display is reported along with a zero-luminance black. Refer to 5.1 for more information regarding zero-luminance blacks. **(3) Scattered Light:** Even when you use a frustum-tube mask stray light in the room can illuminate the front of the LMD and reflect off the screen affecting the results. In such cases it is useful to surround the gap between the frustum-tube mask and the LMD with black cloth or another frustum as shown in FIGURE 5.8. **(4) Measurements without Masks:** Under certain circumstances facilities may wish to make these measurements without the aid of a mask. In such cases, the instrument used will affect the amount of veiling-glare obtained to the measurement of black. If either of the two facilities agree upon the instrument used and the exact geometry and measurement conditions under which the measurement will be made, meaningful comparisons can be obtained between those facilities. For such situations the use of the term “image-signal black” would not be appropriate. Thus, we have included a measurement method for this situation called “Configured Luminance, Color, and Contrast” in the next section, 5.8. **(5) Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see 2.1 Display Description, Identification, and Modes and 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

5.8 Configured Luminance, Chromaticity, and Contrast

DESCRIPTION

We measure luminances, chromaticities, CCTs, or contrasts of a display according to a specific setup condition determined by participating facilities. Symbols: L_{confW} , L_{confK} , u'_{conf} , v'_{conf} and C_{conf} .

These types of measurements are used only when all setup conditions are completely specified and, for example, masks might not be employed to eliminate veiling glare in the detector (see FIGURE 5.9). Configured measurements are often made for ease of implementation and speed of measurement. Such measurement results are never reported in public documents so as to replace better measurement results from superior measurement methods.

SETUP

Any two or more facilities agree upon clearly stated and unambiguous setup conditions in the measurement of display characteristics that include the instrumentation used, the pattern used, the geometry of the setup, and any other pertinent condition that defines the measurement method.

ANALYSIS

The analysis of the resulting data is also clearly and unambiguously specified.



REPORTING

The reporting is also clearly and unambiguously specified and agreed upon between participating facilities.

COMMENTS

Various situations can arise where participating facilities wish to make detailed measurements without the use of masks to avoid veiling glare in the detector as well as other setup conditions. This may be for convenience or for speed of the measurement process. The facilities provide identical setups for comparison purposes. Any other measurement method in this document may be handled in a similar manner where the configuration, analysis, and reporting is completely specified and agreed upon by all participating facilities. In such cases the term “configured” must precede the name of the reported result if they are to appear in any public documentation. For example, “configured viewing angle,” “configured nonuniformity,” “configured contrast,” etc. You’re not reporting it as a public measurement result; the results are private between participating facilities.

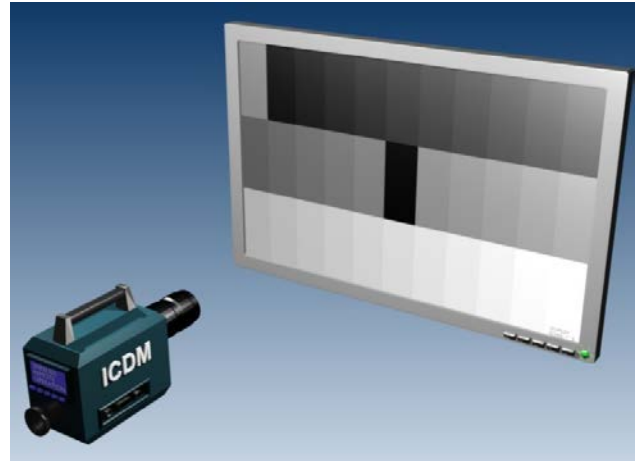


FIGURE 5.9. Configured measurement of luminance of black where a mask is not employed to eliminate veiling glare in the detector. This type of configuration is only used under very special circumstances arranged by participating facilities and the measurement results from such configured measurements are not to be confused with results from better measurement methods.

5.9 Signal Contrast

DESCRIPTION

We calculate the signal contrast based upon the ratio of color-signal white L_{CSW} to image-signal black L_{ISK} that were measured in the previous sections, 5.4 Color-Signal White and 5.7 Image-Signal Black. **Units:** none

Symbol: C_S .

SETUP

None, this is a calculation.

ANALYSIS

The signal contrast is the color-signal white luminance divided by the image-signal black luminance:

$$C_S = \frac{L_{CSW}}{L_{ISK}} \quad (5.10)$$

Please refer to 5.4 Color-Signal White for situations when it is permissible to use full-screen white whereby $L_{CSW} = L_W$ in the above calculation for image-signal contrast.

REPORTING

Report the contrast to no more than three significant figures or the number of significant figures in the black measurement whichever is smaller.

COMMENTS

Undefined Contrasts: As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for image-signal black, it is best to report an “undefined contrast” and include both the white luminance L_{CSW} and the black luminance L_{ISK} in reporting. In no case may the signal contrast be reported as infinite.

TABLE 5.6. Reporting Example: Signal Contrast. <i>Sample data only: Do not use any values shown to represent expected results of your measurements.</i>		
L_{CSW}	213	cd m ⁻²
L_{ISK}	0.12	cd m ⁻²
C_S	1800	



5.9.1 Full-White-Signal Contrast

DESCRIPTION

We calculate the full-white-signal contrast based upon the ratio of full-screen white L_W to image-signal black L_{ISK} that were measured in the previous sections, 5.3 Full-Screen White and 5.7 Image-Signal Black. **Units:** none

Symbol: C_{FWS} .

SETUP

None, this is a calculation.

ANALYSIS

The full-white-signal contrast is the full-screen white luminance divided by the image-signal black luminance:

$$C_{FWS} = \frac{L_W}{L_{ISK}} \quad (5.11)$$

REPORTING

Report the contrast to no more than three significant figures or the number of significant figures in the black measurement whichever is smaller.

COMMENTS

Undefined Contrasts: As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for image-signal black, it is best to report an “undefined contrast” and include both the full-screen-white luminance L_W and the image-signal black luminance L_{ISK} in reporting. In no case may the full-white-signal contrast be reported as infinite.

TABLE 5.7. Reporting Example: Full-White-Signal Contrast. Sample data only: Do not use any values shown to represent expected results of your measurements.		
L_W	244	cd m ⁻²
L_{ISK}	0.121	cd m ⁻²
C_{FWS}	2020	

5.10 Sequential Contrast

ALIAS

darkroom contrast ratio of full screen, full-screen contrast, dynamic contrast

DESCRIPTION

Calculate the sequential contrast based upon full-screen white and full-screen black luminance measurements, L_W and L_K (5.3 and 5.6). **Units:** none, a ratio; **Symbol:** C_{seq} .

ANALYSIS

Sequential-contrast calculation:

$$C_{seq} = \frac{L_W}{L_K} \quad (5.12)$$

REPORTING

Be careful with significant figures. The final reported contrast should have no more significant figures than that of the black luminance measurement.

COMMENTS

(1) **Undefined Contrasts:** As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance

TABLE 5.8. Reporting Example: Sequential Contrast. Sample data only: Do not use any values shown to represent expected results of your measurements.		
L_W	257.2	cd m ⁻²
L_{ISK}	0.142	cd m ⁻²
C_{seq}	1810	



black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. **(2) Contrast**

Characterization: Unless the sequential contrast is the same as the signal contrast, only then can the sequential contrast serve as a single contrast characterization parameter. **(3) Other Contrasts:** Other contrast metrics included in this document are much more useful than sequential or full-screen contrast because of its limited usefulness to scene transitions. The contrast of the screen when there is image content is much more significant.

5.11 Peak Contrast

ALIAS

highlight contrast

DESCRIPTION

We calculate the peak contrast from the Peak White luminance measurement (5.5), L_P , and a black measurement that is the maximum of the Full-Screen Black luminance L_K (5.6) or the Image-Signal Black luminance L_{ISK} (5.7).

Units: None **Symbol:** C_P .

ANALYSIS

The peak contrast is defined as

$$C_P = \frac{L_P}{\max(L_K, L_{ISK})} \quad (5.13)$$

REPORTING

Report the value of peak contrast to no more than two or three significant figures.

COMMENTS

Undefined Contrasts: As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.

5.12 Starfield Contrast

DESCRIPTION

We determine the contrast for a display with content-dependent control (such as dynamic contrast, global dimming, local dimming, etc.) at the threshold of activation of the dynamic control by use of a set of controlled ICDM-provided test patterns to help establish a realistic low level for black content and determining the contrast at the threshold. FIGURE 5.10 shows a typical measurement setup for a star pattern with a center black box; the starfield must be masked off to prevent veiling glare in the detector especially when measuring the black box. The figure shows the use of a SLET (stray-light-elimination tube, see A2.1.5 in the appendix for more information) as an example of several ways to mask the area to be measured.

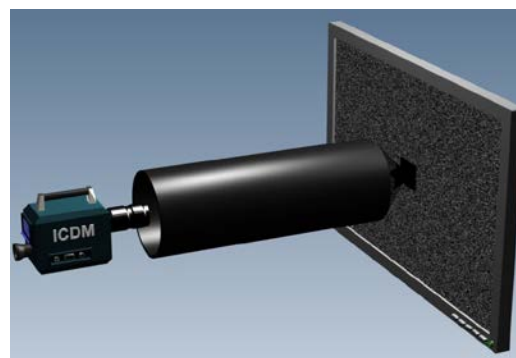


FIGURE 5.10. Starfield contrast measurement setup. A mask must be used for all black measurements so light from the surrounding imagery will not produce veiling glare in the LDM.

FIGURE 5.11 shows a starfield-contrast curve that describes the contrast performance for a display with dynamic contrast. As the content approaches black, the dynamic contrast functionality begins, and the contrast increases



significantly. We look for the point at the knee of the curve to determine the starfield contrast ratio before the rapid increase of contrast. **Units:** none.

Symbols: L_{Wmax} , L_{Wmin} , L_{Kmax} , L_{Kmin} , L_{Wsf} , L_{Ksf} , C_{DC} , C_S

APPLICATION

Primarily for displays which dim the backlight as a function of low luminance content. Notably this is for LCD displays with dynamic contrast (local dimming or global dimming). The starfield patterns provide controlled luminance content (as a % of white) to determine the threshold at which the dimming occurs. At that threshold we calculate the starfield contrast ratio. It can also be used to verify that the black level remains constant for content loading.

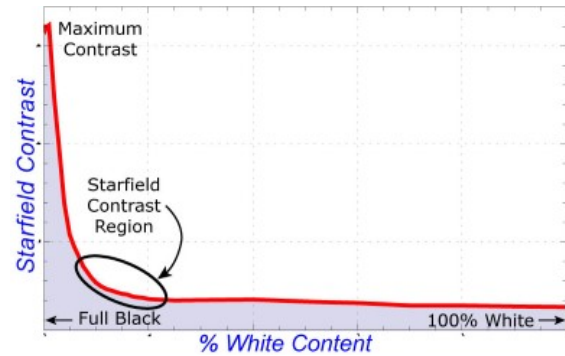
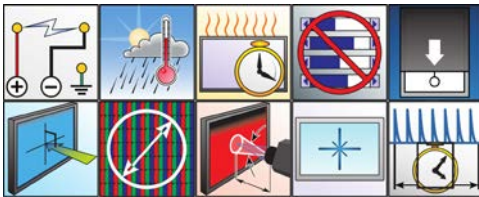


FIGURE 5.11. Starfield contrast curve

SETUP



As defined by these icons, standard setup details apply (3.2). The patterns used are the ICDM starfield contrast ratio pattern set. They are a set of patterns with a controlled amount of white content, from 100 % (full white) to 0 % (full black). They are in pairs, where the same pattern (in terms of % White) has a version with a white center target for measurements and a second version with a black pattern.

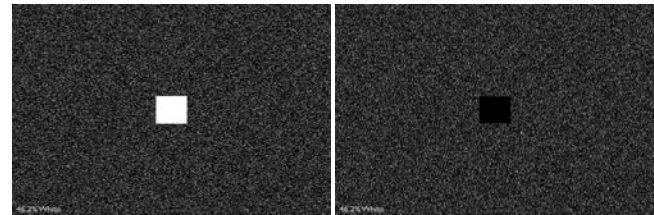


FIGURE 5.12. Example of ICDM starfield contrast patterns showing one starfield contrast pair for 46.2%. Starfield white is on the left and starfield black is on the right. Starfield contrast is the luminance value of the starfield white pattern divided by the luminance of the starfield black pattern at the dynamic contrast cut-off. The patterns are given for a range of white content so that the range of the dynamic contrast displays can be determined, and the cut-off point found.

PROCEDURE

Measure the set of ICDM starlight contrast patterns set for black and for white center targets. The patterns are pairs where one has the center measurement target of white (starfield white patterns) and the other has a black target (starfield black patterns). Measure the white level and the black level at the center screen target for each of the starfield patterns, calculate the starfield contrast, and report the levels. *Caution: You must use a mask to avoid significant measurement errors from veiling glare.*

TABLE 5.9. Reporting Example: Starfield Contrast.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Note that the number of Starfield patterns may vary for some measurement cases.

Pattern		Luminance		Contrast
Step number	% White	Starfield white (cd m ⁻²)	Starfield black (cd m ⁻²)	Starfield contrast
1	100 %(White)	254.4	0.252	1010
2	90	254.6	0.241	1056
3	80	255.6	0.229	1116
4	70	255.4	0.239	1069
5	60	254.8	0.224	1138



6	50	254.2	0.222	1145
7	40	253.8	0.213	1192
8	30	252.6	0.211	1197
9	20	251.7	0.207	1216
10	10	242.5	0.194	1250
11	9	242.5	0.172	1410
12	8	242.4	0.163	1487
13	7	150.1	0.0921	1630
14	6	146.2	0.101	1448
15	5	145.3	0.102	1425
16	4	133.9	0.0933	1435
17	3	117.7	0.0615	1914
18	2	55.01	0.0322	1708
19	1	52.12	0.0212	2458
20	0.5	51.92	0.0198	2622
21	0 % (Black)	51.68	0.0196	2637

TABLE 5.10. Analysis Example: Starfield Contrast.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Description	Value	Pattern
L_{Wmax}	255.6 cd m ⁻²	3
L_{Wmin}	51.68 cd m ⁻²	21
L_{Kmax}	0.252 cd m ⁻²	1
L_{Kmin}	0.0196 cd m ⁻²	21
Full dynamic contrast range (C_{DC}) or $L_{Wmax} L_{Kmin}^{-1}$	13,040	--
White range reduction ratio ($L_{Wmin} L_{Wmax}^{-1}$)	0.2022	--
Black range reduction ratio ($L_{Kmin} L_{Kmax}^{-1}$)	0.08	--
Starfield white (L_{Wsf})	242.4 cd m ⁻²	8
Starfield black (L_{Ksf})	0.163 cd m ⁻²	
Starfield contrast (C_s) or ($L_{Wsf} L_{Ksf}^{-1}$)	1,478	--
Starfield compression ratio ($C_{DC} C_s^{-1}$)	8.823	
ICDM starfield pattern set number	1	--

1. Starfield white: Measure each of the starfield patterns white level in the center of the screen and report them in the table.
2. Starfield black: Measure each of the starfield patterns black level in the center of the screen and report them in the table.
3. We look for the point where the white and black level luminance begins to decrease rapidly at or near the same level. Visually inspect the starfield white data. Determine the point at which it starts to drop in level and add one step. For that step level, report the calculated contrast as the starfield contrast. They must be the same step number. (*Note that for the sample data higher % White levels the luminance per the starfield white pattern remain fairly constant for both black and white.*)

ANALYSIS

Calculate the starfield contrast and other parameters as follows.



1. Full dynamic contrast range: $C_{DC} = L_{Wmax} L_{Kmin}^{-1}$
2. White range reduction ratio: $L_{Wmin} L_{Kmax}^{-1}$
3. Black range reduction ratio: $C_{DC} = L_{Kmin} L_{Kmax}^{-1}$
4. Starfield contrast: $C_s = L_{Wsf} L_{Ksf}^{-1}$
5. Starfield compression ratio: $C_{DC} C_s^{-1}$.
6. Starfield contrast ratio is determined by a change in successive starfield white measurements (as well as successive starfield black measurements and contrast calculations) from the starfield reporting table (TABLE 5.9) where the measured levels change rapidly, decreasing in value for the successive white and black measurements, and increase for the successive contrast calculations.
7. the differences between successive measurements where We look for the point where the white and black level luminance begins to decrease rapidly at or near the same level. Visually inspect the starfield white data. Determine the point at which the value starts to drop in level and add one step. For that step level, report the calculated contrast as the starfield contrast (C_s). The values used (L_{Wsf} and L_{Ksf}) must be at the same step number. *(Note that for the sample data higher percentage white levels the luminance per the starfield white pattern remain fairly constant for both black and white.)*
8. Alternately we can plot the successive starfield white levels (starting from 100 % and decreasing) for starfield white, starfield black, and starfield contrast, and look for the level where difference between successive measurement results is lowest and stays lowest before it starts to increase.

We assess the measured data in the reporting table for the points at which **(1)** the starfield white level sharply decreases, **(2)** the starfield black level rapidly decreases, and **(3)** where the starfield contrast increases. Due to perturbations in the dynamic contrast activation and the limited number of measurement samples, these may not always occur clearly or together.

REPORTING

Report the following quantities:

1. Max. measured white L_{Wmax} and pattern number
2. Min. measured white L_{Wmin} and pattern number
3. Max. measured black L_{Kmax} and pattern number
4. Min. measured black L_{Kmin} and pattern number
5. Starfield white L_{Wsf} and pattern number
6. Starfield black L_{Ksf} (pattern number must be the same as for starfield white)
7. ICDM starlight pattern set number (if applicable)

COMMENTS

We can determine the step level in which the luminance drop-off occurs and starfield contrast is determined in a number of ways:

1. Visual inspection of the measured luminance test results (starting from 100 % white content and decreasing) where we look for the most rapid drop-off of values, typically for the starfield white measured results.
2. Plot of the measured starfield white and black luminance levels (starting from 100% white content and decreasing) and the calculated contrast where the plot shows the points of rapid drop-off. This is typically for starfield white measured results.
3. Plot of the derivatives of the starfield white and black data (starting from 100% white content and decreasing) and the calculated contrast where the luminance drop-off is represented by a high peak, typically for starfield white measured results.



About the starfield contrast patterns: The starfield contrast patterns have a controlled percent of white content per each pattern pair. They are of monochrome content designed to create an appearance of a star field, similar to stars in the sky. A pair consists of two patterns of the same percent white content, but one with a black center target for measurement, and the other with a white target. Thus, by measuring the two, we can divide the luminance of the measured white target by that of the black target, and we get the contrast of the display for that amount of white content.

There is a certain amount of error in the black and white versions of each pattern. The targets are typically 100×100 pixel boxes and are centered in the pattern. The targets introduce a small error in actual percent white, in that they are full white or black for each pattern. In addition, there is an even smaller error introduced by text identifying the pattern in the lower left corner of each pattern. That text is generally a mid-tone gray color to minimize any luminance content imbalance from the percent white content of the patterns.

The amount of error is dependent on the pixel layout of the pattern. For instance, a 1024×768 pixel array starfield contrast pattern with a 100×100 pixel box has a 1.277 % error for the worst case (black target on full white or white target on full black patterns). The error decreases for differing % White patterns and for higher format displays. For 1920×1080 , the error is reduced to 0.482 % worst case. These errors are considered acceptable. We do not recommend that starfield contrast be used for displays with pixel arrays under 1024×768 or the error may become unacceptable.

Note that TABLE 5.9 shows 21 starfield patterns. The number of starfield patterns of the ICDM test pattern set may vary for some measurement cases. Always measure all patterns in the set. Do not make assumptions or interpolate between patterns.

The dynamic contrast of displays varies, and the values of the starfield contrast set are limited, so it is possible that some variation of contrast can occur near the starfield contrast threshold. If that makes it difficult to find the threshold, then the derivative of the curves can help as a tool to locate the correct threshold value.

5.13 Corner-Box Contrast

DESCRIPTION

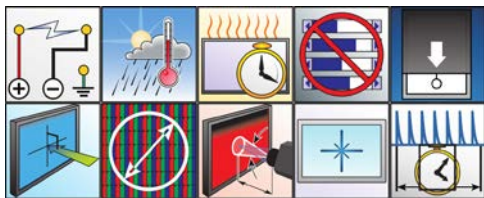
We measure the center contrast of a $0.2 \times$ size white box compared to four $0.1 \times$ size boxes placed in each corner.

Units: None. **Symbol:** C_{CB} .

APPLICATION

This can be applied to any display, but it is especially designed for local dimming displays.

SETUP



As defined by these icons, standard setup details apply (3.2). Use two patterns: One has a $0.2 \times$ size centered box ($0.2H \times 0.2V$) of white on a black background. The other has a black background with $0.1 \times$ size boxes ($0.1H \times 0.1V$) placed in the four corners.

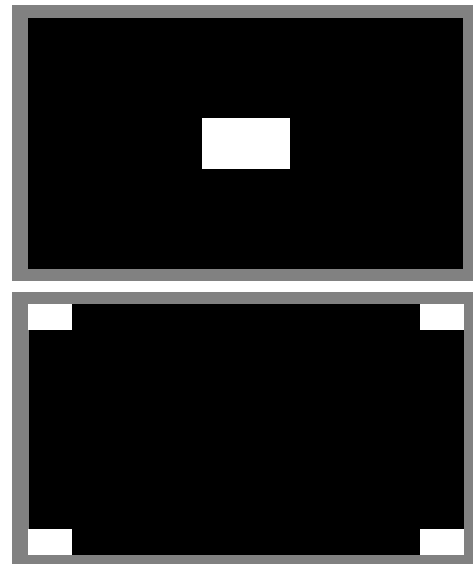


FIGURE 5.13. Top: White center measurement is made on 20% linear box ($0.2 \times$ the size of H and V of display), L_W . Bottom: Black center measurement is made with 10 % linear boxes in corners ($0.1 \times$ size of H and V of display), L_K .



PROCEDURE

Consider using a mask (flat or frustum tube) that does not touch the screen when measuring the black center pattern to be sure that there is no veiling-glare from the white corners when making the black measurement. The mask must not touch the screen.

1. Measure the luminance L_W of the white-center pattern.
2. Measure the luminance L_K of the black-center pattern.

ANALYSIS

Calculate the corner-box contrast

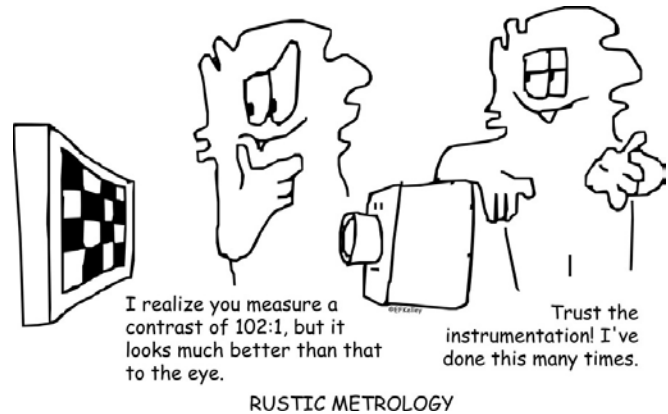
$$C_{CB} = \frac{L_W}{L_K} \quad (5.14)$$

REPORTING

Report the corner-box contrast to no more than three significant figures.

COMMENTS

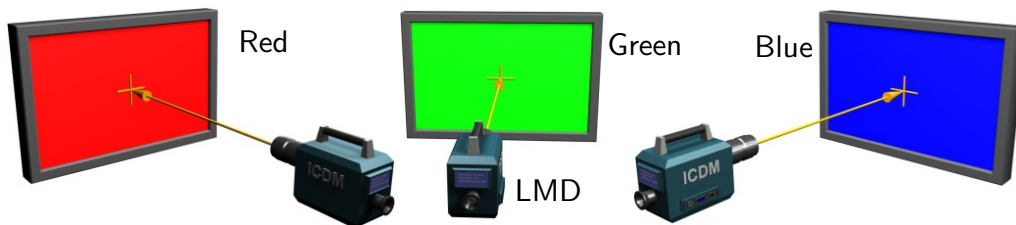
Undefined Contrasts: As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.



5.14 Full-Screen Primary Colors (R, G, and B)

ALIAS

red-, green-, or blue-screen luminance, etc.



DESCRIPTION

Separately measure the luminance and chromaticity coordinates of the full-screen primary (R, G, B) colors. Use the procedure for Full-Screen White 5.3. Use a full-screen pattern of the primary colors, *e.g.*, FR, FG, FB_####x####.PNG.

COMMENT

The chromaticity gamut is the area in a two-dimensional chromaticity diagram—usually CIE 1976 $u'v'$ or CIE 1931 xy —that is defined by the above measured primary colors. The chromaticity gamut area is determined in 5.18 below.

The chromaticity gamut area has been inappropriately referred to as “color gamut” for many years. In addition, it has been plausibly claimed that $u'v'$ area is more appropriate than xy area because of the nominal uniformity of the $u'v'$ chromaticity diagram. However, perceptual color differences in the $u'v'$ diagram depend on luminance. Color is three dimensional. In addition, the chromaticity gamut area metric significantly overestimates the color capability of non-additive display systems. The ICDM now recommends the use of CIELAB color gamut volume and gamut ring metrics as described in Section 5.32. Please also refer to tutorial Chapter 21 on color metrology.



5.15 Full-Screen Secondary Colors (C, M, and Y)

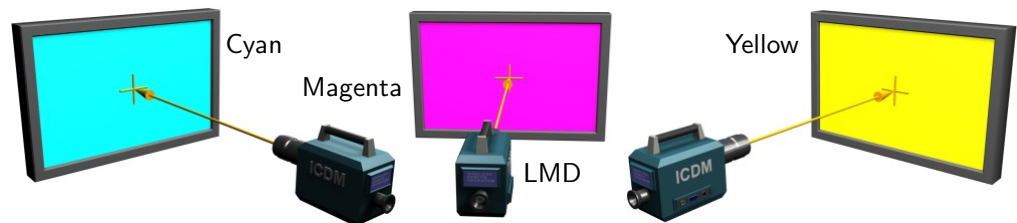
ALIAS

cyan-, magenta-, or yellow-screen luminance, etc.

DESCRIPTION

Separately measure the luminance and chromaticity

coordinates of the full-screen secondary (C, M, Y) colors. Use the procedure for Full-Screen White 5.3. Use a full-screen pattern of the secondary colors, *e.g.*, FC, FM, FY_####x####.PNG.



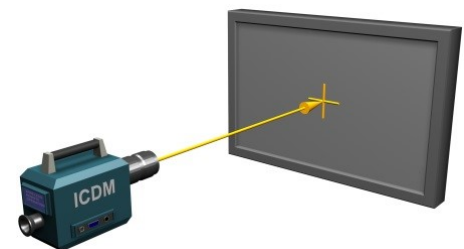
5.16 Full-Screen Grays ($R = G = B = S$)

ALIAS

gray screen, gray-screen luminance

DESCRIPTION

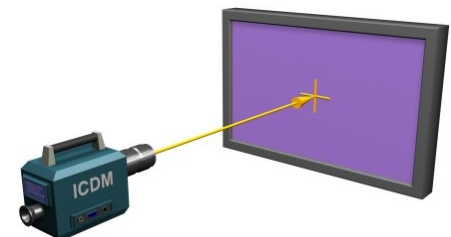
Measure the luminance and chromaticity coordinates of a selected gray shade ($S = R = G = B$). Use the procedure for Full-Screen White 5.3. Use a full-screen gray-shade pattern, *e.g.*, FS#, FS##, FS###_####x####.PNG, where each R, G, B, primary is set at the same color level S .



5.17 Full-Screen Arbitrary Color (R, G, B)

DESCRIPTION

Measure the luminance and chromaticity coordinates of a specified color (R, G, B). Use the procedure for Full-Screen White 5.3. Use a full-screen color pattern where (R, G, B) is specified, *e.g.*, F###-###-###_####x####.PNG. These colors are not duplications of W, K, R, G, B, C, M, Y or S but are intermediate colors within the gamut. Gray levels ($R = G = B$) are a specialized case handled in the previous section. Use the procedure for Full-Screen White 5.3.



5.18 Chromaticity Gamut Area

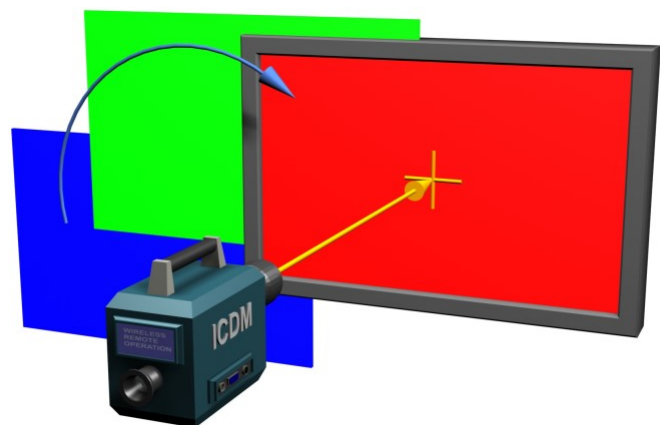
DESCRIPTION

In the CIE 1976 $u'v'$ chromaticity diagram, compute the fraction of chromaticity area A to which the display has access. Chromaticity-coordinate measurements are described in 5.14 Full-Screen Primary Colors (R, G, and B).

Units: none, a percentage. **Symbol:** A .

SETUP

None. This is a calculation based upon chromaticity coordinates measured in 5.14 above.



**PROCEDURE**

If not completed already, measure the chromaticity coordinates of each of the color primaries according to 5.9.

ANALYSIS

If the measurement instrument gives the CIE 1976 (u' , v') coordinates for each of the measured (x , y) values, use these readings. Otherwise, transform each of the (x , y) pairs defined above to (u' , v'), using the following equations

$$u' = \frac{4x}{3 + 12y - 2x} \quad (5.15)$$

$$v' = \frac{9y}{3 + 12y - 2x} \quad (5.16)$$

The area of the RGB triangle in the (u' , v') diagram is $|(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)| \div 2$. We divide this triangle by the area inside the spectrum locus from 380 nm to 700 nm evaluated at 1 nm intervals, which is 0.1952, and multiply by 100 %, to obtain the normalized gamut area (in percent)

$$A = 256.1 |(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)| \quad (5.17)$$

TABLE 5.11. Analysis Example: Chromaticity Gamut Area.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Input	CIE 1931 x	CIE 1931 y	CIE 1931 u'	CIE 1931 v'
Red	0.644	0.342	0.443	0.529
Green	0.304	0.618	0.124	0.567
Blue	0.150	0.043	0.187	0.120
Area, A	36 %			

REPORTING

Report the CIE chromaticity coordinates (x , y)—if measured—and (u' , v') of the primaries, and the computed gamut-area metric A .

COMMENTS

Area gamut is more appropriate than volume gamut when rigorous control is not maintained on the white point and when the display is additive. However, when correlation with volume is necessary, area should instead be calculated in the xy diagram. One uniform-color space, CIELUV, [5.1] has embedded in it a chromaticity space (u' , v') that is used widely in the display industry for such metrics as screen uniformity. [5.2], [5.3] Also, IEC standards specify measurement of chromaticities in (u' , v') coordinates [5.4]. Furthermore, the area in a uniform chromaticity space has long been regarded as a reasonable figure-of-merit for color gamut. [5.5] Therefore, the metric proposed here is the area of the triangle subtended by the primaries (R, G, B) in the chromaticity space whose coordinates are (u' , v').

The chromaticity gamut area has been inappropriately referred to as “color gamut” for many years. In addition, it has been plausibly claimed that $u'v'$ area is more appropriate than xy area because of the nominal uniformity of the $u'v'$ chromaticity diagram. However, perceptual color differences in the $u'v'$ diagram depend on luminance. Color is three dimensional. In addition, the chromaticity gamut area metric significantly over-estimates the color capability of non-additive display systems. The ICDM now recommends the use of CIELAB color gamut volume and gamut ring metrics as described in Section 5.32. Please also refer to tutorial Chapter 21 on color metrology.



REFERENCES

- [5.1] Commission Internationale de l'Eclairage (CIE), Colorimetry (Fourth Edition), *Publication CIE 015:2018*, Bureau Central de la CIE, 2018. DOI: [10.25039/TR.015.2018](https://doi.org/10.25039/TR.015.2018)
- [5.2] P. J. Alessi, CIE guidelines for coordinated research evaluation of colour appearance models for reflection print and self-luminous display image comparisons, *Color Res. Appl.* **19** (1994), 48-58.
DOI: [10.1111/j.1520-6378.1994.tb00060.x](https://doi.org/10.1111/j.1520-6378.1994.tb00060.x)
- [5.3] ISO 9241-305:2008.
- [5.4] IEC 61947-1:2001 (Fixed Resolution Projectors) and IEC 61947-2:2001 (Variable Resolution Projectors).
- [5.5] W. A. Thornton, Color-discrimination index, *J. Opt. Soc. Amer.*, **62** (1972) 191-194.

5.18.1 Relative Chromaticity Gamut Area

The ratio of the gamut area A_{DUT} in the (u', v') diagram of the DUT relative to a chosen (u', v') gamut A_{ref} :
 $G = A_{\text{DUT}} A_{\text{ref}}^{-1}$.

TABLE 5.12. Example of possible gamuts for relative gamut area determinations.

	A_{ref}	White Point			Red		Green		Blue	
	in %	x_W	y_W	Other	x_R	y_R	x_G	y_G	x_B	y_B
sRGB	33.24	0.3127	0.3290	D65	0.6400	0.3300	0.3000	0.6000	0.1500	0.0600
					u'_R	v'_R	u'_G	v'_G	u'_B	v'_B
					0.4507	0.5229	0.1250	0.5625	0.1754	0.1579

A spreadsheet GamutArea.xls for relative gamuts compared to sRGB is available at DOI: [10.55410/njaw6769](https://doi.org/10.55410/njaw6769).

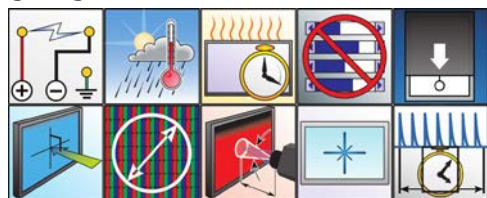
5.19 White-Point Accuracy

DESCRIPTION

We measure the CIE chromaticity coordinates of full-screen white and compute its $u'v'$ distance from a reference white point. If no reference white point is available, compute the full-screen white's correlated color temperature (CCT), compute the CIE chromaticity coordinates of the CIE daylight locus with the same CCT (bounded by two temperature limits), and determine the $u'v'$ distance from the full-screen white to the identified Daylight. (If these measurements have already been made, as in 5.3 or 5.4, then they need not be re-measured here)

Units: CIE 1976 $u'v'$ chromaticity coordinates. **Symbols:** T_C (CCT), $\Delta u'v'$.

SETUP



As defined by these icons, standard setup details apply (3.2).

White full screen test pattern.

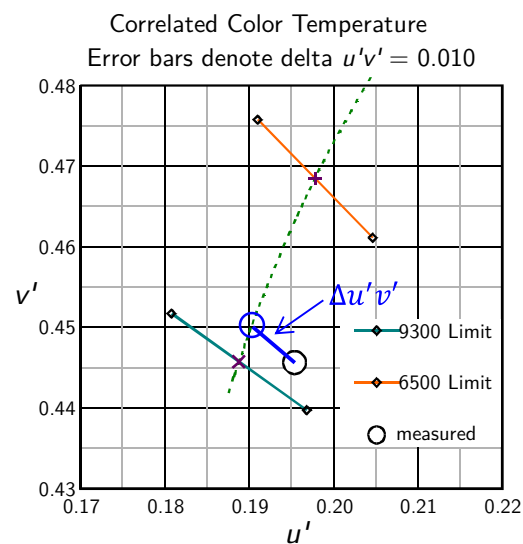


FIGURE 5.14. Sample data only. Distance in $u'v'$ space from measured white to the CIE Standard Daylight that has the same CCT. The dashed line is the CIE daylight locus.



PROCEDURE

Measure the chromaticity coordinates at screen center for a white full screen if it hasn't already been done previously as in 5.3.

ANALYSIS

If a reference white point is available, directly compute the $\Delta u'v'$ distance between the measured chromaticity and that reference white point. In the absence of a reference white point, proceed as follows:

1. Measure the white-point chromaticity (x_W, y_W) and determine the color-temperature limits T_1 and T_2 . Typically, T_1 is 6500 K and T_2 is 9300 K.
2. Compute the CCT (T_C) associated with (x_W, y_W) by McCamy's formula (see Appendix B1.2.1):

$$T = 437n^3 + 3601n^2 + 6861n + 5517, \quad (5.18)$$
where $n = (x_W - 0.3320) \div (0.1858 - y_W)$.
Optionally, use the CCT measurement result if your LMD has that capability.
3. Define the quantity T_b as the closest temperature to CCT (T_C) that is between T_1 and T_2 : If $T < T_1$, set $T_b = T_1$. If $T > T_2$, set $T_b = T_2$, otherwise, set $T_b = T$.

4. Use formulas 5(3.3.4) and 6(3.3.4) in Wyszecki and Stiles, *Color Science* (pp. 145-146, second Ed., Wiley, 1982) to compute the point (x_b, y_b) on the CIE daylight locus that is associated with CCT T_b . First, define

$g = 1000 \div T_b$, then

$$\text{if } T_b < 7000, \text{ then } x_b = -4.6070g^3 + 2.9678g^2 + 0.09911g + 0.244063 \quad (5.19)$$

$$\text{if } T_b > 7000, \text{ then } x_b = -2.0064g^3 + 1.9018g^2 + 0.24748g + 0.237040 \quad (5.20)$$

5. In either case, $y_b = -3000x_b^2 + 2.870x_b - 0.275$. In later steps, this chromaticity (x_b, y_b) is to be compared with the chromaticity (x_W, y_W) of the measured screen white.
6. Convert (x_W, y_W) and (x_b, y_b) to $u'v'$ coordinates

$$(u'_W, v'_W) = (4x_W, 9y_W) \div (3 + 12y_W - 2x_W) \quad (5.21)$$

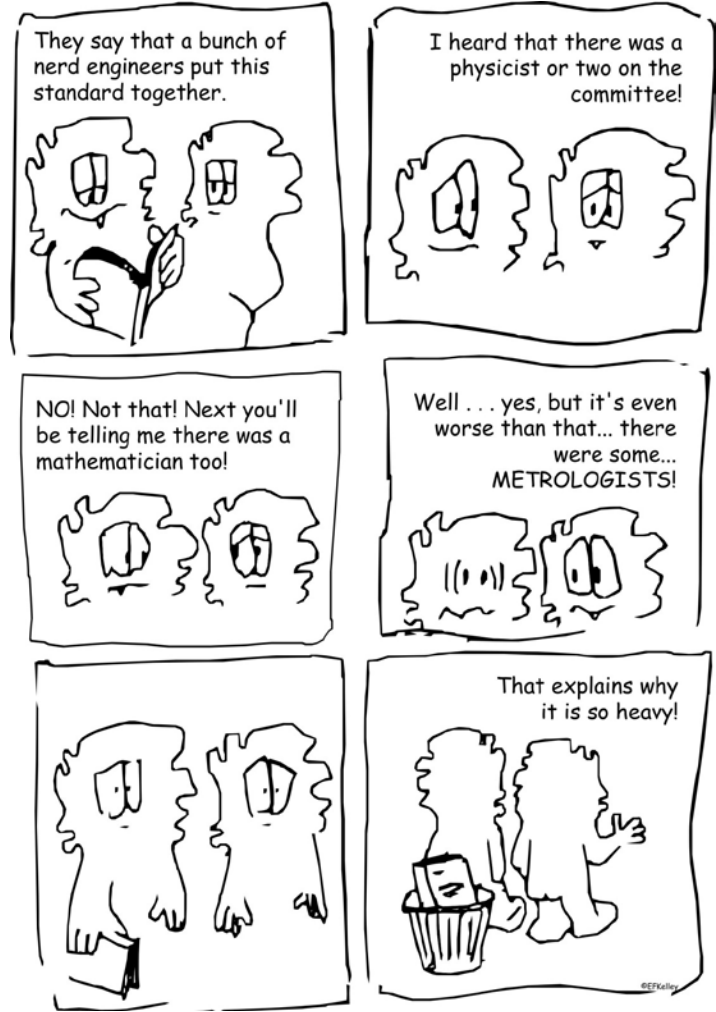
$$(u'_b, v'_b) = (4x_b, 9y_b) \div (3 + 12y_b - 2x_b) \quad (5.22)$$
7. Evaluate $\Delta u'v'$ between (u'_W, v'_W) and (u'_b, v'_b):

$$\Delta u'v' = \sqrt{(u'_W - u'_b)^2 + (v'_W - v'_b)^2} \quad (5.23)$$

A template for calculating the white-point accuracy is available at <https://doi.org/10.55410/tbnv1171>

REPORTING

Report the CIE chromaticity coordinates of white (x_W, y_W), the correlated color temperature (CCT) T_C , and the distance $\Delta u'v'$ from the designated point on the daylight locus. For example: If the input screen-white is (x, y) = (0.39, 0.31), $T_1 = 6500$ K, and $T_2 = 9300$ K; then the CCT is $T_C = 3054$ K, $T_b = 6500$ K, and $\Delta u'v' = 0.0648$.





COMMENTS

In Steps 2–4 in the above analysis, the CCT is defined by a computation in CIE 1960 (u, v) chromaticity diagram, but in steps 5–6 the modern distance is computed in CIE 1976 (u', v') chromaticity diagram. In step 4, note that the formulas are 5(3.3.4) and 6(3.3.4) in G. Wyszecki and W. Stiles, *Color Science* (pp. 145-146, second ed., Wiley, 1982). Also note that the CIE daylight locus used in Steps 4-7 is not quite the same as the black-body locus that defines CCT and is implicitly used in Step 3; in fact, the motivation of this computation is to transfer the reference-white chromaticity from the black-body locus (where it was prior to 1976) to the daylight locus (where it is preferred today). Finally, note that a fairly restricted temperature range (T_1, T_2) is recommended, because temperatures much outside this range, *e.g.*, yellow or red, do not represent credible screen whites; that is, the chosen range reflects the domain over which target monitor white points are commonly chosen.

5.20 CCT White-Point Validation

ALIAS

CCT offset from the Planckian Locus

DESCRIPTION

We calculate the $\Delta u'v'$ distance of a measured white point (FIGURE 5.15) with chromaticity coordinates (u'_W, v'_W) from the point on the Planckian (black-body) locus (u'_P, v'_P) having the same CCT T_W . **Units:** K (kelvin) for CCT, none for $\Delta u'v'$. **Symbols:** (u'_W, v'_W) for the measured white point, (u'_P, v'_P) for the point on the Planckian locus having the same CCT. This calculation is alternative to White-Point Accuracy (5.19), in which the deviation of the white point is calculated from the daylight locus rather than from the Planckian locus.

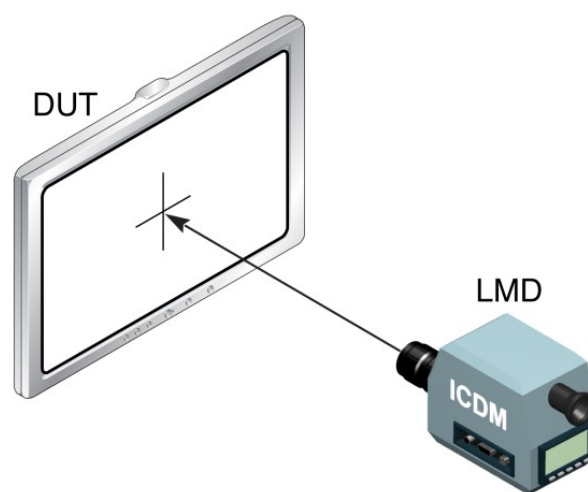


FIGURE 5.15. White-screen

SETUP

As defined by these icons, standard setup details apply (3.2).



PROCEDURE and ANALYSIS

If the white point chromaticity coordinates have already been measured, they need not be measured again in which case proceed to step 2.

1. Measure the chromaticity coordinates (u'_W, v'_W) of a full-screen white pattern, or one that will not reduce maximum luminance level for a display with luminance loading.
2. Calculate the CCT of T_W from the following equation. Here is the full equation in a very small font

$$T_W = \frac{(146412.7u'_W + 59239.9)v'_W{}^2 - 179737u'_W(u'_W + 0.0149665)v'_W + 51869.926(u'_W - 0.1827208)u'_W(u'_W + 0.579256) - 92672.7v'_W{}^3 - 21306.03v'_W + 3133.488}{(0.5574u'_W - 3.4864v'_W + 1.1148)^3} \quad (5.24)$$

Here is the same equation with the numerator wrapped around for clarity.



$$T_W = \frac{\left[(146412.7u'_W + 59239.9)v'_W{}^2 - 179737u'_W(u'_W + 0.0149665)v'_W + 51869.926(u'_W - 0.1827208)u'_W(u'_W + 0.579256) - 92672.7v'_W{}^3 - 21306.03v'_W + 3133.488 \right]}{(0.5574u'_W - 3.4864v'_W + 1.1148)^3} \quad (5.25)$$

3. From the CCT T_W use the following equations to find the chromaticity coordinates (u'_P, v'_P) for the same CCT on the Planckian locus. Note: Use the u'_P and v'_P calculations only in the range of $1000 \text{ K} \leq T_W \leq 15000 \text{ K}$.

$$u'_P = \frac{(128.641 \times 10^{-9})T_W^2 + (154.118 \times 10^{-6})T_W + 860.118 \times 10^{-3}}{(708.145 \times 10^{-9})T_W^2 + (842.42 \times 10^{-6})T_W + 1} \quad (5.26)$$

$$v'_P = \frac{(63.0723 \times 10^{-9})T_W^2 + (63.4209 \times 10^{-6})T_W + 476.098 \times 10^{-3}}{(161.456 \times 10^{-9})T_W^2 - (28.9742 \times 10^{-6})T_W + 1} \quad (5.27)$$

$$\Delta u'v' = \sqrt{(u'_P - u'_W)^2 + (v'_P - v'_W)^2} \quad (5.28)$$

REPORTING

Report (u'_W, v'_W) , CCT (T_W), and $\Delta u'v'$. Optionally specify $\Delta u'v'$ thresholds, determine if the calculated value is within those limits, and report that as pass or fail.

COMMENTS

(1) The Euclidean distance $\Delta u'v'$ indicates how far off from the Planckian locus the measured (u'_W, v'_W) values are. When we combine the CCT with the $\Delta u'v'$, we can determine at what limit the CCT is or is not useful or realistic for defining a white point. (2) Equations (5.26) and (5.27) are from Krystek, Michael P. (1985). “An algorithm to calculate correlated colour temperature.” *Color Research and Application* **10** (1): 38–40. DOI:[10.1002/col.5080100109](https://doi.org/10.1002/col.5080100109). Krystek’s equations are for 1960 uv space. In Eqs. (5.26)–(5.27), Krystek’s v equation is multiplied by 1.5 to convert it to v' . The u equation is identical for u or u' .

- (3) If (x_W, y_W) are measured, use the transformation equations in Appendix B1.2 to obtain (u', v') as follows

$$u' = \frac{4x}{3+12y-2x}, v' = \frac{9y}{3+12y-2x}.$$

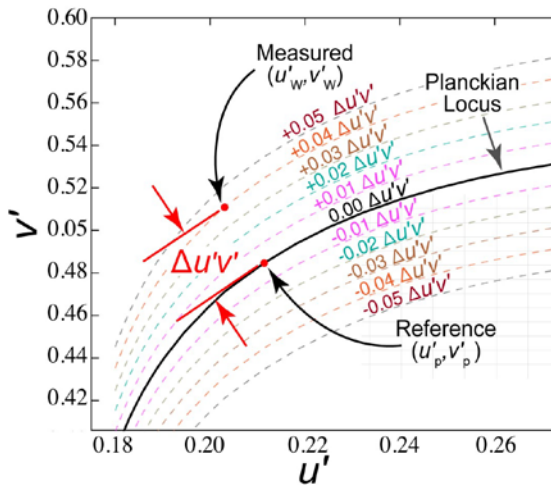


FIGURE 5.16. Example showing a measured (u'_W, v'_W) point and a reference point (u'_P, v'_P) exactly on the Planckian locus with the $\Delta u'v'$ showing how far the measured point is from the same CCT point on the Planckian locus.

TABLE 5.13. Analysis example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Item	Measurements	Value
u'_W (u' measured)	0.2056	--
v'_W (v' measured)	0.5355	--
Calculations		
CCT (T)	4090.7	K
u'_P (u' on locus)	0.2236	--
v'_P (v' on locus)	0.4998	--
$\Delta u'v'$	0.0399	--
Optional: Specified $\Delta u'_t v'_t$ threshold	0.xxxx	--
Is the calculated $\Delta u'v'$ within the threshold limit? $\Delta u'v' \leq \Delta u'_t v'_t$	pass / fail	--



5.21 Luminance Adjustment Range

ALIAS

dimming range, brightness (see comment 3 of 5.3) range, dimming ratio

DESCRIPTION

Here we measure the luminance adjustment range from maximum and minimum luminance (if such an adjustment is provided) using the center measurement of a white full screen. **Units:** none, expressed in percentage. **Symbol:** none.

The luminance adjustment range is the extent to which the full-screen white luminance of a DUT may be adjusted between maximum and minimum brightness with the gray-scale capability preserved as per the setup gray scale (33 or 32 gray shades, or however many gray shades that are agreed upon by all interested parties).

APPLICATION

NOTE: Adjustment of controls can possibly invalidate all previous measurements. We suggest that you perform this measurement during setup (but after warm-up) or make it the last measurement made. If additional luminance (or chromaticity) measurements are to be made, the display must be returned to its proper setup configuration for normal operation under standard conditions. This section applies only for displays that have luminance adjustment capabilities. Luminance adjustment may be implemented in various ways (via software control or in hardware), such as by a potentiometer, or by digitally interfaced implementations as with keyboard keystrokes.

SETUP

As defined by these icons, standard setup details apply (3.2).



Display full-screen white during the test. For displays having additional adjustments that can affect the luminance adjustments, the contrast should be pre-adjusted as per the setup chapter (3) and should not be touched during this measurement. However, certain displays are deliberately adjusted to retain the gray scale while the luminance of the full-screen white is adjusted. If such a gray-level preservation adjustment is made, it must be fully described in the reporting document. On some displays, the controls can be manipulated to, in effect, turn the display off. The gray scale must be preserved for all luminance levels employed for the defined task.

Note: If other measurements must be made after this test it is important to document the control settings prior to adjustment by whatever mechanical or software method available as well as a luminance measurement of the gray scale, so that the DUT can be returned to the luminance and gray scale it exhibited before this measurement. See the Setup Chapter 3 for any standard setup details.

PROCEDURE

Record the maximum luminance on the reporting sheet (L_{\max}). Adjust luminance for minimum. Allow for luminance stabilization as per the standard warm-up time (20 min), then measure luminance. Report this number as minimum luminance level (L_{\min}).

ANALYSIS

The Adjustment range is the percentage of reduction of luminance from maximum to minimum luminance. It can be calculated as follows.

$$\% \text{Adjustment} = 100\% \frac{L_{\max} - L_{\min}}{L_{\max}} \quad (5.29)$$



Where %Adjustment is the luminance adjustment range, and L_{\max} and L_{\min} the maximum and minimum luminance, respectively.

REPORTING

Report maximum luminance level (L_{\max}), minimum luminance level (L_{\min}), then calculate and report luminance adjustment range (%Adjustment). For example, for a DUT that has maximum luminance of 200 cd m^{-2} and minimum luminance of 20 cd m^{-2} , the adjustment range is 90 %.

COMMENTS

On many technologies, it is important to allow the DUT adequate warm-up time for each luminance level setting before measurements are made, just as when the DUT is first turned on.

5.22 Large-Area Full-Screen Center Measurement

ALIAS

full-screen large-area measurements

DESCRIPTION

Measure the large area luminance and chromaticity coordinates of full screen white, black, and the color primaries red, green, and blue at the center of the screen. Measure the correlated color temperature (CCT) for white. **Units:** cd m^{-2} for the luminance of the primaries, kelvin (K) for CCT, and none for the chromaticity coordinates.

Symbols: L_i , x_i , y_i , where i refers to either white, black, red, green, or blue. T_C for CCT.

APPLICATION

All large-sized displays which have no luminance level changes for full screen content (no luminance loading).

SETUP



As defined by these icons, standard setup details apply (3.2).

Normal measurement distance for this test is 3.0 m minimum. Move the LMD away from the monitor until a large measurement area of the display is targeted. Unlike traditional full-screen measurements which use a recommended measurement distance of 500 mm for a 2° nominal aperture, with less than 10% of horizontal and vertical dimensions, the purpose of this test is to measure more than 50% of the horizontal and vertical dimensions as aspect ratio permits. You can increase the distance up to a point where the edge of the measurement aperture area is within 5% of the edge of the active area of the display, as limited only by measurement room measurement range. This measurement can be made in the portrait or landscape mode

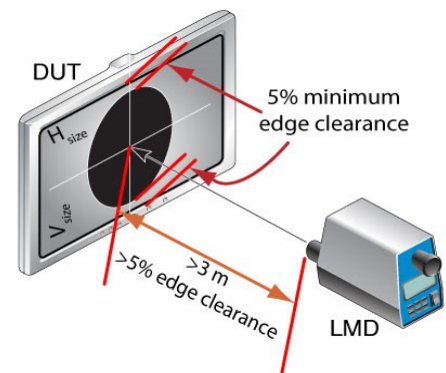


FIGURE 5.17. Experimental setup.

TABLE 5.14. Chromaticity coordinates of the reference signal.

Variable Name	Value
x_{Rn}	0.67
y_{Rn}	0.33
x_{Gn}	0.21
y_{Gn}	0.71
x_{Bn}	0.14
y_{Bn}	0.08



PROCEDURE

1. Set up the detector to measure the center of the display, perpendicular to it at a measurement distance of 3 m or greater. Obtain the chromaticity coordinates of the reference signal being used to display the colors.
2. Measure all the parameters of the large-area full screen center measurement for the center of the screen and report them in a data collection exemplified by TABLE 5.15
3. Full screen white - Luminance, chromaticity coordinates
4. Full screen black – Luminance
5. Full screen red - Luminance, chromaticity coordinates*
6. Full screen green - Luminance, chromaticity coordinates*
7. Full screen blue - Luminance, chromaticity coordinates*
8. Measure the distance from the LMD lens to the center of the screen and report.
9. Report the active area of the display

*Chromaticity coordinates can be (x, y) or (u', v') . They must be consistent. Do not mix them within this test.

†Calculate the contrast and add it to the data collection table: $C = L_W L_K^{-1}$

‡Relative chromaticity gamut area is calculated as follows.

Use the 1931 (x, y) coordinates. If the values in TABLE 5.15 or TABLE 5.14 are reported in (u', v') , first convert them to (x, y) . Calculate the relative gamut area as follows and add it to the data collection sheet.

$$G = 100\% \left| \frac{(x_R - x_B)(y_G - y_B) - (x_G - x_B)(y_R - y_B)}{(x_{Rn} - x_{Bn})(y_{Gn} - y_{Bn}) - (x_{Gn} - x_{Bn})(y_{Rn} - y_{Bn})} \right| \quad (5.30)$$

ANALYSIS

Geometry is analyzed as shown in the reporting section.

Total number of pixels

$$N_T = N_H N_V \quad (5.31)$$

DUT diagonal in mm

$$D_{\text{mm}} = D \times 25.4 \text{ mm in}^{-1} \quad (5.32)$$

Measurement field diameter in mm

$$D_{\text{MF}} = 2000z \tan \frac{\theta_{\text{MFA}}}{2}, z \text{ in m} \quad (5.33)$$

Horizontal screen size in mm

$$H = \sqrt{\frac{D_{\text{mm}}^2 N_H^2}{N_H^2 + N_V^2}} \quad (5.34)$$

Vertical screen size in mm

$$V = \sqrt{D_{\text{mm}}^2 - H^2} \quad (5.35)$$

Total area of the display in cm^2

$$A = HV \div (10 \text{ mm cm}^{-1})^2 \quad (5.36)$$

Measurement field diameter in pixels

$$d_{\text{px}} = d_{\text{MF}} N_H H^{-1} \quad (5.37)$$

Total pixels under the measurement field

$$N_{\text{MF}} = \frac{\pi}{4} d_{\text{px}}^2 \quad (5.38)$$

TABLE 5.15. Analysis example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

	Item	Result	Units
White	L_W	243.7	cd m^{-2}
	x_W	0.3362	
	y_W	0.3671	
	T_C	5360	K
Black	L_K	0.54	cd m^{-2}
	$L_W L_K^{-1}$	451.29	
Red	L_R	56.35	cd m^{-2}
	x_R	0.6493	
	y_R	0.3353	
Green	L_G	165.60	cd m^{-2}
	x_G	0.3035	
	y_G	0.6124	
Blue	L_B	21.46	cd m^{-2}
	x_B	0.1437	
	y_B	0.0939	
Relative gamut area CIE 1931 (x, y)		70.66	%



Area of the measurement field in cm^2

$$A_{\text{MF}} = \frac{\pi}{4} (0.1 d_{\text{MF}})^2 \quad (5.39)$$

% area covered by measurement field

$$A_{\text{rel}} = 100\% N_{\text{MF}} N_{\text{T}}^{-1} \quad (5.40)$$

REPORTING

1. Enter the setup conditions onto the reporting sheet.
2. N_{H} Number of horizontal pixels.
3. N_{V} Number of vertical pixels.
4. D Diagonal size of the screen in inches.
5. θ_{MFA} Measurement field angle in degrees.
6. z distance from LMD to the DUT in m.
7. Calculated items: Calculate the values from TABLE 5.16 and enter them onto the reporting sheet.

COMMENTS

None.

The chromaticity gamut area has been inappropriately referred to as “color gamut” for many years. In addition, it has been plausibly claimed that $u'v'$ area is more appropriate than xy area because of the nominal uniformity of the $u'v'$ chromaticity diagram. However, perceptual color differences in the $u'v'$ diagram depend on luminance. Color is three dimensional. In addition, the chromaticity gamut area metric significantly over-estimates the color capability of non-additive display systems. The ICDM now recommends the use of CIELAB color gamut volume and gamut ring metrics as described in Section 5.32. Please also refer to tutorial Chapter 21 on color metrology.

TABLE 5.16. Reporting example. <i>Sample data only: Do not use any values shown to represent expected results of your measurements.</i>			
Setup Items to report	Symbol	Value	Unit
	N_{H}	1280	pixels
	N_{V}	1024	pixels
	D	17	inches
	θ_{MFA}	2	degrees
	z	4.572	M
Calculated Results	N_{T}	1 310 720	pixels
	D_{mm}	431.8	Mm
	d_{MF}	159.61	Mm
	H	337.179	Mm
	V	269.743	Mm
	A	909.517	cm^2
	d_{px}	605.91	pixels
	N_{MF}	288339	pixels
	A_{MF}	200.1	cm^2
	A_{rel}	22.0	%

5.23 Halation

DESCRIPTION

We measure the luminance of a black box with a white background as the size of the box is adjusted from a small fraction of the screen to full screen.

WARNING

VEILING-GLARE CORRUPTION. MASK REQUIRED

Halation is said to occur when light from surrounding white areas corrupts a black area on the screen. This measurement is a method to characterize the amount of halation for a black box at the center of a white screen.

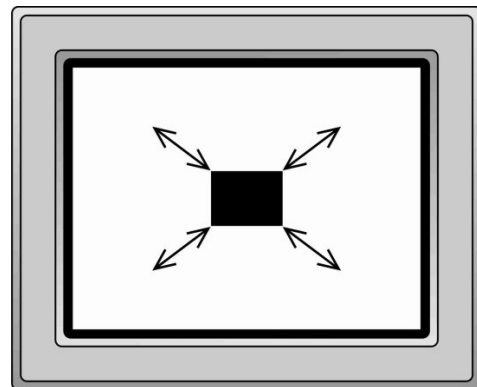
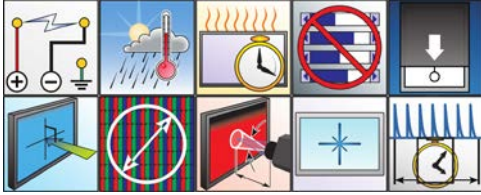


FIGURE 5.18. Expanding black box on white background for halation measurement.



SETUP

As defined by these icons, standard setup details apply (3.2).



Arrange for a box to vary in size from 5 % of the screen diagonal to the full screen. Use a frustum mask to eliminate any veiling glare in the detector (LMD)— see Appendix A2 Stray-Light Management and Veiling Glare.

PROCEDURE

Use a sequence of centered black boxes on a white background with the size of the boxes being $kH \times kV$ where $k = 0.05, 0.1, 0.2, \dots, 0.9, 1.0$. Plot the luminance of the box vs. the area of the box (HVk^2) or the luminance of the box vs. the k factor (%), which is percent of diagonal or decimal.

ANALYSIS

Calculate the ratio of the difference between maximum box luminance L_{\max} and the full-screen black luminance L_K to the full-screen white luminance L_W as the halation \mathcal{H} in percent:

$$\mathcal{H} = 100\% \frac{L_{\max} - L_K}{L_W}$$

REPORTING

Report the full-screen white and black luminances, the minimum box size used, the maximum box luminance (usually the smallest box), and the resulting halation.

COMMENTS

Be sure to use a frustum mask or equivalent to eliminate veiling glare. See Appendix A2 Stray-Light Management and Veiling Glare.

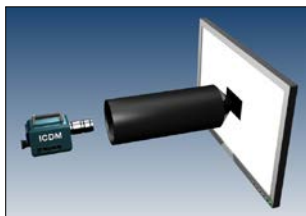


FIGURE 5.20. Example of a frustum-tube mask. To avoid reflections from the room illuminating the front of the LMD wrap the LMD-tube gap with black cloth.

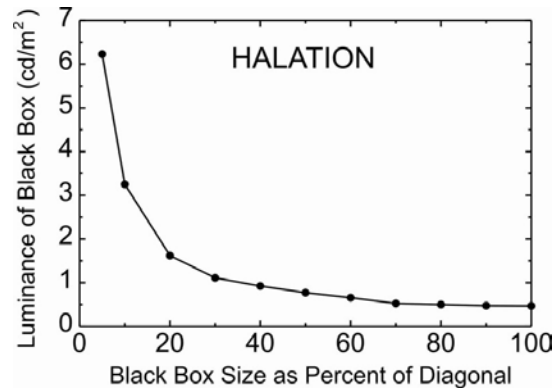


FIGURE 5.19. Example of halation data.

Sample data only: Do not use any values shown to represent expected results of your measurements.

TABLE 5.17. Reporting example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Symbol	Value	Unit
L_W	95.7	cd m ⁻²
L_K	0.468	cd m ⁻²
Min. Box	5	%
L_{\max}	6.23	cd m ⁻²
Halation, \mathcal{H}	6.0	%

TABLE 5.18. Analysis example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

White (L_W)	95.7
Box % Diag.	L_{box} (cd m ⁻²)
5 % (L_{\max})	6.23
10 %	3.25
20 %	1.62
30 %	1.11
40 %	0.923
50 %	0.769
60 %	0.655
70 %	0.523
80 %	0.498
90 %	0.473
100 % (L_K)	0.468
Halation	6.0 %



5.24 Loading

ALIAS

luminance loading, screen loading

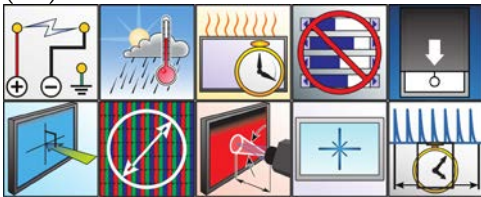
DESCRIPTION

We measure the luminance of a white box with a black background as the size of the box is adjusted from a small fraction of the screen to full screen.

Luminance loading is said to occur when the luminance of a white area on a screen changes as the white area changes its size. In some cases, this can have a desirable effect, in other cases it can be objectionable. This method is a way to characterize the effect of luminance loading.

SETUP

As defined by these icons, standard setup details apply (3.2).



Arrange for a box to vary in size from 5 % of the screen diagonal to the full screen.

PROCEDURE

Use a white box on a black background. Start with full-screen white and go down to $0.05H \times 0.05V$ as with halation (previous measurement, 5.23); measure the luminance L_{box} of the center of each box. Plot the results. Note that it is advisable to employ a mask (frustum tube mask suggested) to avoid veiling-glare contributions from the larger white boxes—see Appendix A2 Stray-Light Management and Veiling Glare.

ANALYSIS

Calculate the ratio of the difference in percent of the extreme luminance value from the full-screen white, L_{ext} , and the luminance of full-screen white, L_W . The loading \mathcal{L} is

$$\mathcal{L} = 100\% \frac{(L_{\text{ext}} - L_W)}{L_W}$$

REPORTING

Report the full-screen white, the minimum box size used, the maximum box luminance (usually the smallest box), and the resulting loading.

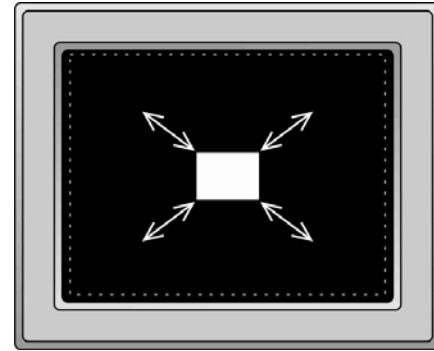


FIGURE 5.21. Expanding white box for loading measurement.

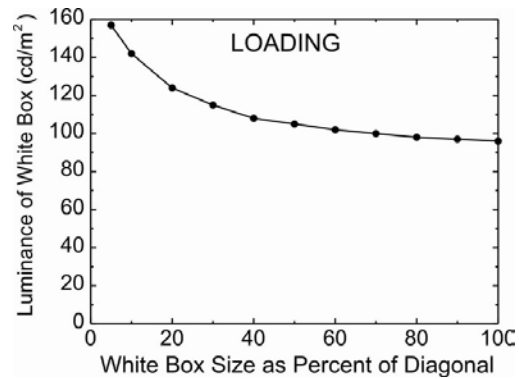


FIGURE 5.22. Example of loading.

TABLE 5.19. Analysis example – Sample Data.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Box % Diagonal	L_{box} (cd m ⁻²)
5 % (L_{ext})	157
10 %	142
20 %	124
30 %	115
40 %	108
50 %	105
60 %	102
70 %	100
80 %	98.1
90 %	97.3
100 % (L_W)	96.2
Loading, \mathcal{L}	63 %



COMMENTS

It can be useful to employ a frustum mask or equivalent to eliminate the slight veiling glare in the detector (LMD) that can occur as the box increases in size. See Appendix A2 Stray-Light Management and Veiling Glare.

5.25 Simple Box Measurements

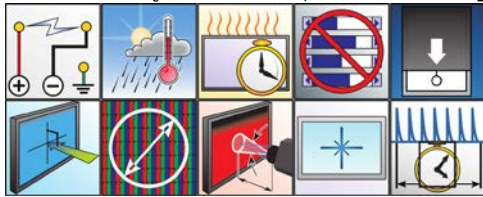
Note: This main section (5.25) describes a generic measurement method that is implemented in each of the following subsections. The specific patterns to be used are listed under these separate subsections.

GENERAL DESCRIPTION

We measure the luminance L and optionally the chromaticity coordinates and color temperature at the center of a centered box one fifth (or optionally one sixth) the linear size of the screen.

SETUP

As defined by these icons, standard setup details apply (3.2).



Use appropriate patterns for each subsection. Note that if the background is not black, it may be advisable to use a frustum mask or equivalent to eliminate any veiling glare in the detector (LMD) that arises from light coming from the background area.

PROCEDURE

Measure desired characteristics of the box.

ANALYSIS

None

REPORTING

Report the box color, the background color, and other appropriate measured quantities.

COMMENTS

Note that CCT measurements only apply to near white colors.

L_W (cd m ⁻²)	96.2
Min. box	5 %
L_{ext} (cd m ⁻²)	157
Loading, \mathcal{L}	63 %

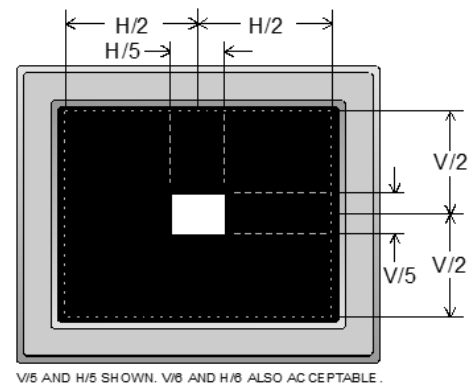


FIGURE 5.23. Typical box-measurement configuration.

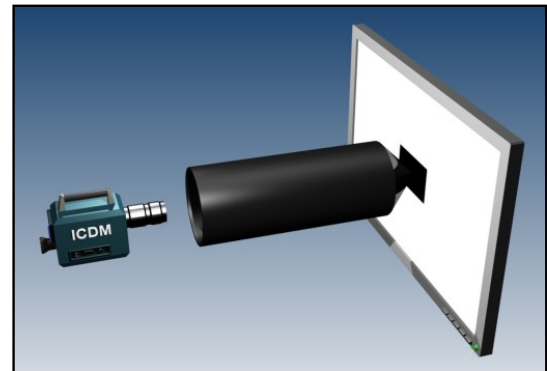


FIGURE 5.24. Whenever the background is not black or very dark gray, a frustum mask of some type (or equivalent) should be used to eliminate any veiling glare in the detector (LMD)—see Appendix A2 Stray-Light Management and Veiling Glare.



TABLE 5.21. Reporting example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Box Color	white	
Background Color	black	
L_{box}	182	cd m^{-2}
CIE 1931 x_{box}	0.3195	
CIE 1931 y_{box}	0.3544	
$T_{\text{C,box}}$	6070	K

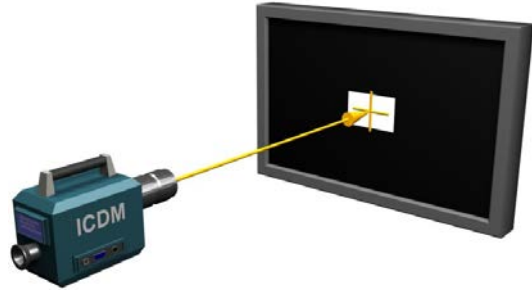
5.25.1 White Box on Black

ALIAS

white box luminance, white window luminance

See General Description at the beginning of this main section

5.25 Simple Box Measurements for general details. Use a pattern with a 20 % white box (4 % area) on a black background (e.g., XW_####x####.PNG).

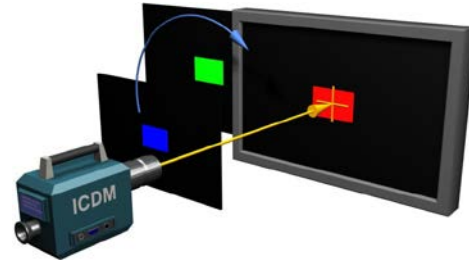


ADDITIONAL COMMENTS

Box White Versus Peak or Highlight White: To accommodate displays where a peak or highlight white is even brighter than this box white, we provide a peak luminance (5.5) and contrast (5.11) to characterize such displays. However, if the highlight or box luminance and contrast is reported, it must be labeled “box” or “highlight” luminance or contrast, and the full-screen white luminance must be also reported as “full-screen white luminance.” This way, the impression is not left with the user that the full-screen white is at the level of the highlight white.

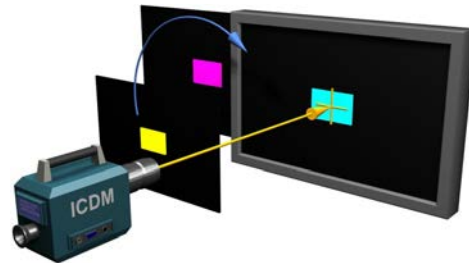
5.25.2 Primary Color (RGB) Box on Black

See General Measurement Description at the beginning of this main section 5.25 Simple Box Measurements for general details. Use a pattern with a 20 % primary-color box (4 % area) on a black background, e.g., XR, XG, XB_####x####.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.



5.25.3 Secondary Color (CMY) Box on Black

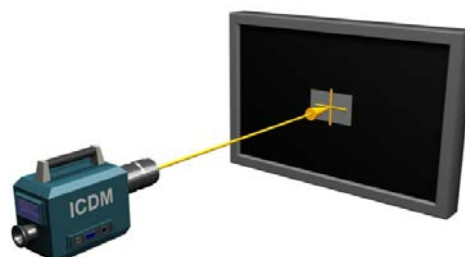
See General Measurement Description at the beginning of this main section 5.25 Simple Box Measurements for general details. Use a pattern with a 20 % secondary-color box (4 % area) on a black background, e.g., XC, XM, XY_####x####.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.





5.25.4 Gray ($R = G = B = S$) Box on Black

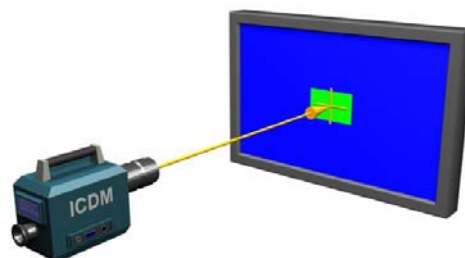
See General Measurement Description at the beginning of this main section 5.25 Simple Box Measurements for general details. Use a pattern with a 20 % gray box (4 % area) on a black background, *e.g.*, X20S#, X20S##, X20S###_####x####.PNG) where each R , G , B , primary is set at the same level S .



5.25.5 Color (R,G,B) Box on Background (R_b, G_b, B_b)

See General Measurement Description at the beginning of this main section 5.25 Simple Box Measurements for general details.

Use a pattern with a 20 % colored box (4 % area) where the color (R , G , B) is specified for the box and a different color (R_b, G_b, B_b) is specified for the background. These colors are not duplications of W, K, R, G, B, C, M, Y, nor are they gray levels ($R = G = B$) but are intermediate colors within the gamut. Veiling glare corruption is possible for luminance and the measured chromaticity. A mask is suggested.



WARNING: VEILING-GLARE CORRUPTION POSSIBLE — MASK ADVISED

5.25.6 Black Box on White

See General Measurement Description at the beginning of this main section 5.25 Simple Box Measurements for general details.

Use a pattern with a 20 % black box (4 % area) on a white background. A gloss-black frustum (or equivalent) that prevents any of the white-screen light from reaching the detector (either from near the box or from the edges of the screen) *must* be used to prevent veiling-glare corruption of the measurement of the black box. A smaller gloss-black frustum with a matte-black tube may also be used—see Appendix A2: Stray-Light Management for more details.



WARNING: VEILING-GLARE CORRUPTION POSSIBLE — MASK ADVISED

5.26 Checkerboard Luminance and Contrast ($n \times m$)

DESCRIPTION

We measure the black and white luminances at the vicinity of the center of a checkerboard pattern and calculate the contrast.

The specification $n \times m$ is the number of columns (n) by the number of rows (m). There are several types of checkerboards. One has even rows and columns in each dimension. Another has odd rows and columns in each dimension. Most will use either the even or odd patterns. There are two types that mix even and odd that will probably be rarely, if ever, used. The only type of checkerboard what will be measured using only one pattern is the even checkerboard. All the other types (containing an odd component) require two with one being the negative of the



other. In the figure we show some examples for illustration. The contrast is $C_C = L_W L_K^{-1}$, where L_W and L_K are either the center measurements in the case of the odd checkerboard or averages of white and black boxes about the center in all other cases

$$\text{ODD} \quad C_C = \frac{L_W}{L_K} \quad (5.41)$$

$$\text{EVEN and EVEN/ODD} \quad C_C = \frac{L_{WL} + L_{WR}}{L_{KL} + L_{KR}} \quad (5.42)$$

$$\text{ODD/EVEN} \quad C_C = \frac{L_{WT} + L_{WB}}{L_{KT} + L_{KB}} \quad (5.43)$$

Here, the first letter in the subscript refers to black or white, and the second letter in the subscript is “L” for left, “R” for right, “T” for top, and “B” for bottom. See FIGURE 5.25.

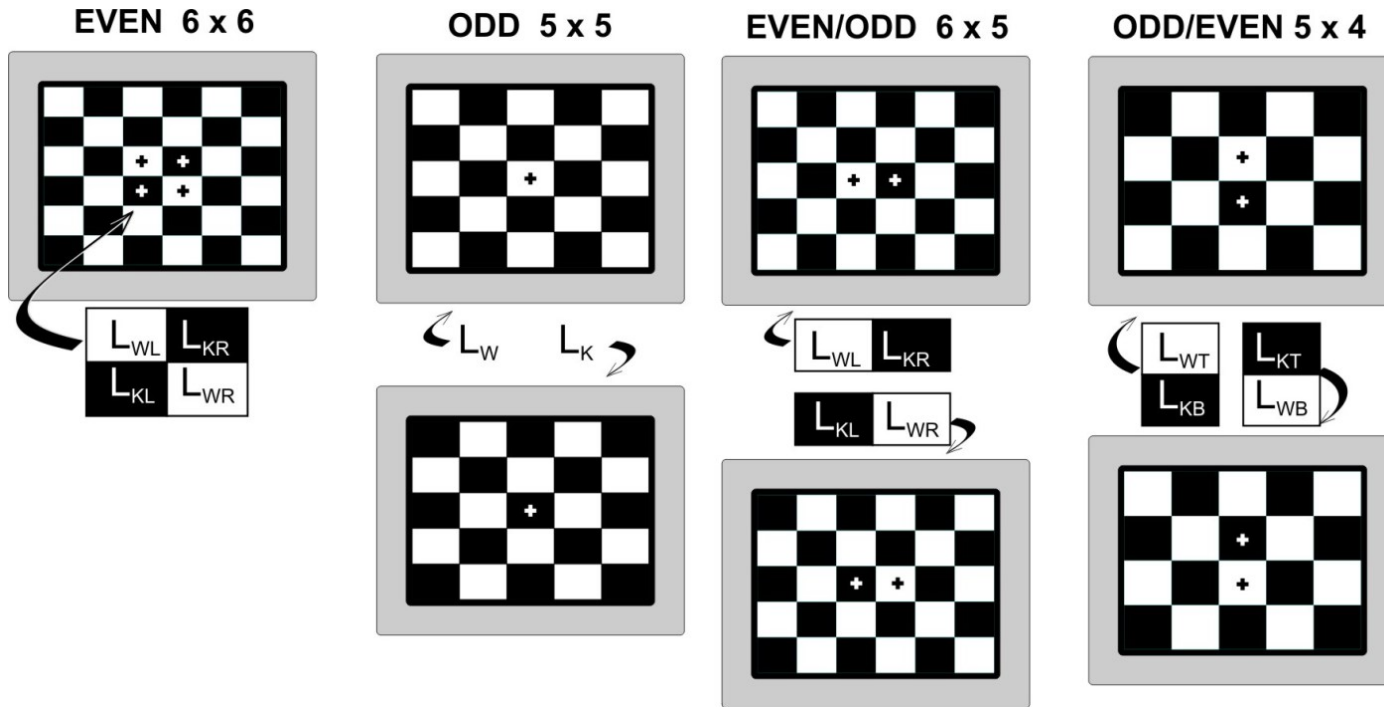
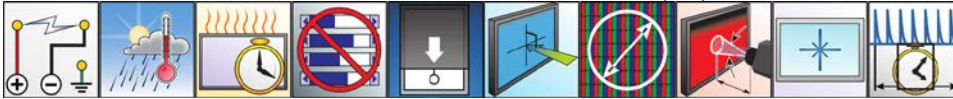


FIGURE 5.25. Checkerboard patterns for contrast measurements

SETUP

As defined by these icons, standard setup details apply (3.2).



Arrange to measure the black and white luminances at the center of the boxes at or in the vicinity of the center of a checkerboard pattern. If either the number of columns or the number of rows is odd, then the negative of the pattern must also be measured.



TABLE 5.22. Summary of checkerboard formats.

Checkerboard Pattern		Required patterns	White	Black	Contrast
Columns	Rows		L_W	L_K	$C_C = L_W L_K^{-1}$
Even	Even	1	$L_{WL} + L_{WR}$	$L_{KL} + L_{KR}$	$C_C = \frac{L_{WL} + L_{WR}}{L_{KL} + L_{KR}}$
Odd	Odd	2	L_W	L_K	$C_C = \frac{L_W}{L_K}$
Even	Odd	2	$L_{WL} + L_{WR}$	$L_{KL} + L_{KR}$	$C_C = \frac{L_{WL} + L_{WR}}{L_{KL} + L_{KR}}$
Odd	Even	2	$L_{WT} + L_{WB}$	$L_{KT} + L_{KB}$	$C_C = \frac{L_{WT} + L_{WB}}{L_{KT} + L_{KB}}$

PROCEDURE

Display the desired checkerboard pattern. The luminances are measured at the center of the boxes ($\pm 3\%$ of the screen diagonal) nearest the center of the screen according to the scheme shown in the figure (the “+” signs indicate the measurement positions). For *even* checkerboards measure the luminance at the center of the four boxes positioned next to the center of the DUT. For *odd* checkerboards measure at the center of the screen for each of the two (negative and positive) patterns obtaining the black and white luminance directly. For *even/odd* checkerboards measure the luminance of black and white on each side of the center of the screen for both the negative and positive patterns. For *odd/even* checkerboards measure the luminance of black and white above and below the center of the screen for both the negative and positive patterns.

ANALYSIS

See TABLE 5.22 for an outline of the procedure. For *even*, *even/odd*, and *odd/even* checkerboards, using the appropriate formula in equations (5.41)-(5.43), obtain the average of the black and white recorded luminances then calculate the contrast. For *odd* checkerboards calculate the contrast between the black and white luminances from the two patterns.

REPORTING

Report the $n \times m$ checkerboard used, the black luminance, the white luminance, and the checkerboard contrast to no more than three significant figures. Use the average luminance values when reporting the black and white luminances for the even, even/odd, or odd/even checkerboards.

TABLE 5.23. Analysis – Sample Data.

Do not use any values shown to represent expected results of your measurements.

Even Checkerboard				Odd Checkerboard		Reporting	
Checkerboard		6×6		Checkerboard	5×5	Checkerboard	5×5
L_{WL}	101	L_{KL}	0.451	L_W	103	L_W	103
L_{WR}	105	L_{KR}	0.477	L_K	0.464	L_K	0.464
L_W	103	L_K	0.464	C_C	245	C_C	245
CC		245					

COMMENTS

1. **Undefined Contrasts:** As discussed in 5.1 Fundamental Measurements, if a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.
2. **Veiling Glare:** Be careful in making the black measurement. Avoid glare corruption of black by using a black-gloss frustum mask. See A2 Stray-Light Management and Veiling Glare for details on measurements of black in



the presence of white. Some will want to measure all the checkerboard rectangles and base the contrast on an average value C_{Cave} over the entire screen.

3. **Gray Levels:** There may be instances where a white and black checkerboard is not as useful as a checkerboard composed of two different gray shades (or even colors). There can be no objection to such modifications provided all interested parties are agreeable, and the modification is clearly documented in any report. Some will want to measure all the checkerboard rectangles and base the contrast on an average value C_{Cave} over the entire screen. Some will want to measure a wider or different sampling of rectangles than just at the center and report their averages. Provided all interested parties agree and the modifications are clearly stated and reported, there is no objection to such modifications.

5.27 Box Sequential Contrast

This measurement is included for reasons of legacy (FPDM2 304-2). We recommend 5.11 Peak Contrast as a replacement for this method.

ALIAS

centered box on-off luminance and contrast

DESCRIPTION

We measure the contrast ratio of a white centered box 1/5 to 1/6 the size of the diagonal against a full black screen (optionally a black box on white screen).

Units: None. **Symbol:** C_B .

Box contrast ratios can be different than full-screen darkroom contrast ratios because of loading effects of the display or other factors. Sometimes it is desired to know how the performance of the display changes from full screen to a small area. The box contrast is the ratio of luminance of the white box to the luminance of the black background $C_B = L_W L_K^{-1}$. This is the negative pattern (white box on black). Additionally, a positive pattern can be employed to determine the box contrast for a black box on a white screen $C'_B = L_W L_K^{-1}$, or the positive pattern. To avoid unreasonable or infinite contrasts, it may be wise to use $\max(L_K, L_{KCS})$ instead of L_K as with 5.11 Peak Contrast.

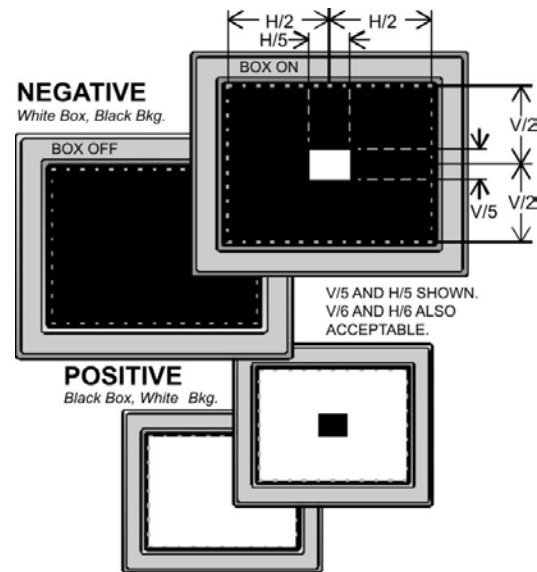


FIGURE 5.26. Measurement pattern and locations

SETUP

As defined by these icons, standard setup details apply (3.2).



Arrange to measure the center luminance of a white box centered on the screen and a black screen without the box. The box should be in the range of 1/5 to 1/6 of the diagonal of the screen.

PROCEDURE

Measure the luminance of the center of the box L_W . Turn off the box and measure the luminance of the full black screen L_K .



ANALYSIS

Calculate the contrast ratio: C_B (and optionally C'_B).

REPORTING

Report the contrast ratio as the on-off box contrast ratio.

COMMENTS

(1) Undefined Contrasts: As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. **(2) Rectangle Sizes:** Other sizes of rectangles may be used provided they are agreeable to all interested parties and are clearly reported in any document.

TABLE 5.24. Reporting example. <i>Do not use any values shown to represent expected results of your measurements.</i>	
L_W	0.732
L_K	94.3
C_B	129

5.28 Contrast of Centered Box

This measurement is included for reasons of legacy (FPDM2 304-1). We recommend 5.11 Peak Contrast as a replacement for this method.

ALIAS

luminance and contrast of centered box

DESCRIPTION

We measure the luminance of the center of a white centered box 1/5 to 1/6 the size of the diagonal with a black background. (Optionally: a black box of the same size on a white background.) The surrounding black screen is measured at eight positions and the average, maximum, and minimum contrast is calculated.

Units: none. **Symbol:** C_B .

Box contrast ratios can be different than full-screen darkroom contrast ratios because of loading effects of the display. Sometimes it is desired to know how the contrast performance of the display changes from full screen to a small area. To avoid unreasonable or infinite contrasts, it may be wise to use $\max(L_K, L_{KCS})$ instead of L_K as with

5.11 Peak Contrast.

SETUP

As defined by these icons, standard setup details apply (3.2).



Pattern: Centered white box on black (optionally black box on white). Arrange to measure the center luminance of a white box centered -on the screen (negative pattern) and the surrounding black area. (Optionally a positive pattern with a black box with a white background may additionally be measured.) The box should be in the range of 1/5 to 1/6 the diagonal of the screen. Arrange to measure the surrounding black area at eight points surrounding the white box at a distance of the size of the box from the center of the screen (see FIGURE 5.27).



PROCEDURE

Measure the luminance of the center L_C of the box where we define $L_C \equiv L_5$. For contrast measurements, determine the luminance of the black surround at the eight points (L_i , $i = 1, 2, 3, 4, 6, 7, 8, 9, i \neq 5$) half the thickness of the box away from the box (see FIGURE 5.27). Be sure to avoid glare contamination of the black measurement. It is suggested that a black-gloss cone mask be used to prevent glare. See A2 Stray-Light Management and Veiling Glare for details on measurements of black in the presence of white.

ANALYSIS

Calculation of the contrast ratio given by the white luminance divided by the black luminance: $C_B = L_W L_K^{-1}$. The box contrast ratio is the average of the eight readings. Also determine the maximum and minimum contrasts

C_{Bmax}, C_{Bmin} .

Negative: White box on black background:

$$C_B = \frac{8L_C}{\sum_{i \neq 5} L_i}, C_{Bmin} = \frac{L_C}{L_{max}}, C_{Bmax} = \frac{L_C}{L_{min}} \quad (5.44)$$

Optionally: *Positive*: Black box on white background:

$$C'_B = \frac{1}{8L'_C} \sum_{i \neq 5} L'_i, C'_{Bmin} = \frac{L'_{min}}{L'_C}, C'_{Bmax} = \frac{L'_{max}}{L'_C} \quad (5.45)$$

where the implicit sum is over $i = 1, 2, 3, 4, 6, 7, 8, 9, i \neq 5$, L_{min} and L_{max} are the minimum and maximum luminances of the eight black luminance measurements made in the black background, $L_{min} = \min(L_i)$, $L_{max} = \max(L_i)$.

Similarly, if the positive pattern is (optionally) also measured, L'_{min} and L'_{max} are the minimum and maximum white luminance of the eight white luminance measurements made in the white background.

REPORTING

Report the luminance of the centered box. For contrast measurements, report the luminance of the eight black readings and the separate contrasts obtained. Also report the average as the box contrast ratio C_B . Report all contrasts to no more than three significant figures. Be sure that the significant figures of the box contrast ratio do not exceed the significant figures of the black measurements.

COMMENTS

(1) **Undefined Contrasts:** As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case

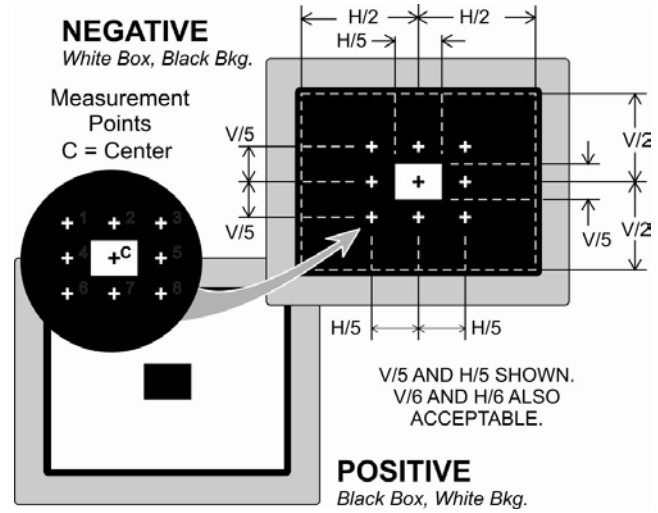


FIGURE 5.27. Measurement pattern and locations.

TABLE 5.25. Analysis and Reporting of Sample Data. Do not use any values shown to represent expected results of your measurements.		
Pattern	Negative: White on Black	
Black at 1	Black at 2	Black at 3
0.45 cd m ⁻²	0.71 cd m ⁻²	0.42 cd m ⁻²
330:1	210:1	360:1
Black at 4	White luminance	Black at 6
0.68 cd m ⁻²	151 cd m ⁻²	0.62 cd m ⁻²
220:1	Ave.: $C_B = 270:1$	240:1
Black at 7	Black at 8	Black at 9
0.49 cd m ⁻²	0.64 cd m ⁻²	0.51 cd m ⁻²
310:1	230:1	290:1



may the contrast be reported as infinite. (2) **Veiling Glare:** Be careful of making black measurements in the presence of white. See A2 Stray-Light Management and Veiling Glare for details. Be careful with the use of masks since reflections off the mask can also corrupt the black measurement. A black-gloss frustum mask is suggested.



RUSTIC METROLOGY



5.29 Transverse Contrast of Centered Box

This measurement is included for reasons of legacy (FPDM2 304-3). We recommend 5.11 Peak Contrast as a replacement for this method.

ALIAS

JEITA's window contrast ratio.

DESCRIPTION

We measure the contrast ratio of a centered box $1/5$ to $1/6$ the size of the diagonal of the screen by measuring the luminance L_W of the center of the white box (box on = white) and measure the luminance L_K of the black at the same position with the box off (or full-screen black).

NOTE: This measurement is a subset of or contained within the measurements specified in 5.28 Contrast of Centered Box.

There are two configurations: negative, with a black background and white box; and the (optional) positive, with white background and black box. The contrasts of the negative box C_B and the positive box C'_B are given by

$$C_B = \frac{2L_C}{L_L + L_R}, C'_B = \frac{L_L + L_R}{2L_C} \quad (5.46)$$

where L_C is the luminance at the center position, L_L is the luminance at the left position, and L_R is the luminance at the right position. (The factor of two comes from the average of the two background measurements.) To avoid unreasonable or infinite contrasts, it may be wise to use $\max(L_K, L_{KCS})$ instead of L_K as with 5.11 Peak Contrast.

SETUP

As defined by these icons, standard setup details apply (3.2).



Arrange to measure the center luminance of a white box centered on a black screen (negative pattern) and, optionally, the positive pattern. The box should be in the range of $1/5$ to $1/6$ of the diagonal of the screen.

PROCEDURE

Measure the center luminance of the white box. Then measure the black luminance of each horizontal side of the box at a distance of one half the box size from the edge of the box.

ANALYSIS and REPORTING

Calculate the box contrast C_B according to the above equations. (Optionally add C'_B .)

COMMENTS

(1) **Undefined Contrasts:** As discussed in 5.1 Black and White Characterization Issues, if a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite. (2) **Veiling Glare:** Be careful

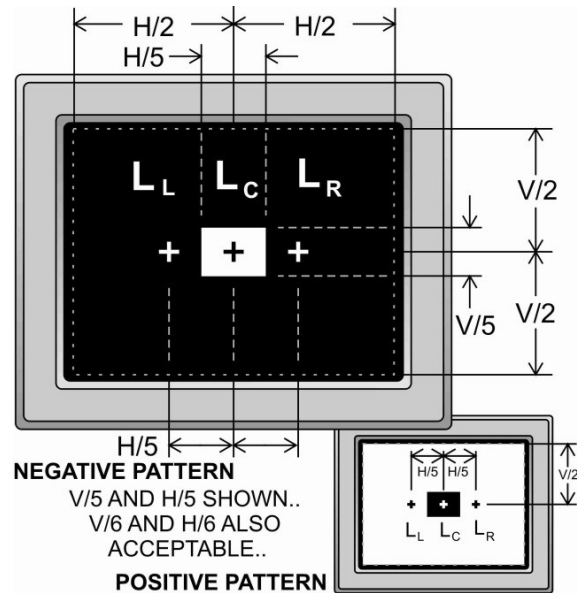


FIGURE 5.28. Measurement pattern and locations.



in making the black measurement. Avoid glare corruption of black by using a black-gloss cone mask. See A2 Stray-Light Management and Veiling Glare for details on measurements of black in the presence of white.

5.30 Perceptual-Contrast Length

ALIAS: perceptual contrast

DESCRIPTION

Perceptual-contrast length is calculated for characterization of stimulus contrast capability of a display by using the difference of black and white brightness. Luminances of black and white are measured at a centered window occupying 4% of the screen area with a 40% gray-level background, *e.g.*, gray level 102 of 0 to 255 levels. Perceptual contrast length is calculated based on the Bartleson-Breneman model.

Units: None. **Symbol:** l_{PC} .

APPLICATION

This method is useful for evaluation of displays showing videos and/or broadcast images due to its inclusion of the concept of stimulus contrast, and the wide range of luminance levels inherent in this type of content.

SETUP

As defined by these icons, standard setup details apply (3.2):



PROCEDURE

1. Measure the luminance levels of black, L_K , and white, L_W , in the 4% window box at the center of the screen against the 40% gray-level background, *e.g.*, gray level 102 on a scale of 0 to 255 levels for an eight-bit display. Note that a mask or stray-light-elimination tube may be required to prevent veiling glare in the detector when measuring the black box. Note that we show a measurement of black and white in the sample data, but in step 2 below we show how to make this calculation for any color Q that you wish to use.

2. The measured luminance for black and white shall be transformed into brightness as follows:
Applying the Bartleson-Breneman model, for any color Q calculate its brightness B_Q from its luminance L_Q as:

$$B_Q = \frac{10^{2.037} L_Q^{0.1401}}{\text{antilog}_{10}[g \times e^{f \log_{10} L_Q}]} \quad (5.47)$$

where

$$g = 0.99 + 0.124 L_W^{0.312}, \quad f = -0.1121 - 0.0827 L_W^{0.093},$$

L_W : White luminance of the scene in cd m^{-2} ,

L_Q : Luminance of a scene color Q element in cd m^{-2} .

Note: Black and white color Q elements are used but B_Q may be calculated for a chosen color as well.

3. Compute the perceptual contrast length with brightness of black and white.

ANALYSIS

Calculate the perceptual contrast length by using the brightness of black and white: $l_{PC} = B_W - B_K$.

Table 5.26. Analysis example.
Do not use any values shown to represent expected results of your measurements.

	L (cd/m ²)	B
Black	0.8575	1.23
White	607.1	32.23



REPORTING

As in the sample TABLE 5.27.

COMMENTS

Compared to simple measurements of contrast ratio, the Bartleson-Breneman model describes human perception of brightness quite well under a wide range of ambient illumination conditions, including darker ambient conditions (such as below 150 lux). Brightness is the attribute of a visual sensation to which an area appears to emit more or less light. Bartleson and Breneman applied experimental results of scaled brightness perception in complex fields to the analysis of display reproduction. [5.6]. More comprehensive predictions of surround effects on perceived contrast are provided by Color Appearance Models (Hunt, RLAB, and CIECAM) [5.7].

REFERENCES

- [5.6] C. J. Bartleson and E. J. Breneman, “Brightness Perception in Complex Fields,” J. Opt. Soc. Am. 57, 953-957 (1967) DOI: [10.1364/JOSA.57.000953](https://doi.org/10.1364/JOSA.57.000953).
- [5.7] M. D. Fairchild, Color Appearance Models, 2nd Ed., John Wiley and Sons, pp. 125-127 (2005). DOI: [10.1002/9781118653128](https://doi.org/10.1002/9781118653128)

5.31 Volume-Color-Reproduction Capability

DEPRECATED: Use the method in section 5.32 to measure CIELAB Gamut Volume.

Section 5.31 is retained here for legacy purposes; it is not intended to be used anymore. Section 5.32 is compatible and consistent with other standards organizations’ definitions of CIELAB Color Volume, including those from the CIE. Section 5.32 addresses the shortcomings of prior methods by providing proper chromatic adaptation to a single reference volume and by properly evaluating color volumes of any arbitrary shape. Results from 5.32 can be used in comparison studies for different types of displays. Additionally, 5.32 provides derivative volume metrics, notably volume intersection to a reference and gamut rings, that can be useful for evaluating and comparing the color capability of different displays.

DESCRIPTION

An approximate color gamut volume is calculated for characterization of color reproduction capability of a display in a three-dimensional color space. Luminance and chromaticity of colors are measured at a centered window occupying 4% of the screen area with 40% gray level background, *e.g.*, gray level 102 of 0 to 255 levels. NOTE: Color gamut volume is calculated in the CIELAB, CIELUV, or other perceptually uniform color spaces. The selected color space shall be noted in the report.

Unit: ΔE^3 **Symbol:** V_{CRC} .

APPLICATION

This method is particularly important for displays showing video and/or broadcast images, owing to the wide range of luminance levels inherent in the content of those images.

TABLE 5.27. Reporting example. <i>Do not use any values shown to represent expected results of your measurements.</i>	
Perceptual Contrast Length	
l_{PC}	31.0

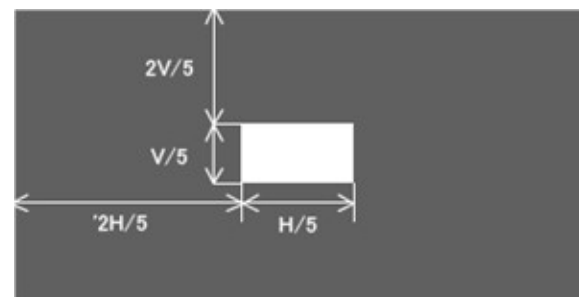


FIGURE 5.29. Test pattern.



SETUP

As defined by these icons, standard setup details apply (3.2):



PROCEDURE

1. Apply each of the following eight colors in the 4% window box at the center of the screen against the 40% gray-level background, *e.g.*, gray level 102 of 0 to 255 levels for an eight-bit display (see FIGURE 5.29):

Red (255, 0, 0)	Magenta (255, 0, 255)
Green (0, 255, 0)	Yellow (255, 255, 0)
Blue (0, 0, 255)	Cyan (0, 255, 255)
White (255, 255, 255)	Black (0, 0, 0)

Note that it may be necessary to use some kind of a mask or stray-light-elimination tube to avoid veiling glare in the detector when measuring black.

2. Measure the luminance and chromaticity coordinates or tristimulus values of each color.
3. The measurement data for all defined colors shall be transformed (see appendix B1.2 if you need help on these conversions) into the three-dimensional color space as follows:
- 4.

For CIELAB, calculate as

$$L^* = 116 \times f(YY_n^{-1}) - 16 \quad (5.48)$$

$$a^* = 500 \times [f(XX_n^{-1}) - f(YY_n^{-1})] \quad (5.50)$$

$$b^* = 200 \times [f(YY_n^{-1}) - f(ZZ_n^{-1})] \quad (5.51)$$

$$\text{where } f(t) = \begin{cases} t^{1/3} & t > (6/29)^3 \\ \frac{1}{3} \left(\frac{29}{6}\right)^2 t + \frac{16}{116} & \text{otherwise} \end{cases} \quad (5.53)$$

and (X_n, Y_n, Z_n) is (475.228, 500, 544.529), which is based on sRGB white point (0.3127, 0.3290) of (x, y) chromaticity coordinates and 500 cd m⁻² white luminance.

For CIELUV, calculate as

$$L^* = \begin{cases} \left(\frac{29}{3}\right)^3 \frac{Y}{Y_n}, \frac{Y}{Y_n} \leq (6/29)^3 \\ 116 \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16 \frac{Y}{Y_n} > (6/29)^3 \end{cases} \quad (5.49)$$

$$u^* = 13L^*(u' - u'_n) \quad (5.52)$$

$$v^* = 13L^*(v' - v'_n) \quad (5.54)$$

where (u'_n, v'_n) is sRGB white point (0.1978, 0.4683) of (u', v') chromaticity coordinates and Y_n is white 500 cd m² luminance.

5. Calculate the color gamut volume corresponding to the possible range of display colors as represented in the defined color space in the next section on Analysis.

ANALYSIS

1. Calculate the 17 interpolated gradation points between black and the other six primary and secondary (RGBYMC) colors using a gamma of 2.2

$$L_{Qn} = (L_{Q\max} - L_{Q\min}) \left(\frac{n}{255}\right)^{2.2} + L_{Q\min} \quad (5.55)$$



where $L_{Q_{\max}}$ is the maximum luminance for a measured color Q and where $n = \{0, 17, 33, 49, 65, 81, 97, 113, 129, 144, 160, 176, 192, 208, 224, 240, 255\}$ and $L_{Q_{\min}}$ is the measured black luminance. This creates 102 points (17 levels \times 6 primary and secondary colors = 102 total). Add the measured white (W) point for a total of 103 points.

2. Transform tristimulus values (X, Y, Z) of all 103 points to the defined color space.
3. The scattered 102 points, not including white, in the three-dimensional space are projected onto the (a^*, b^*) plane in the case of CIELAB or are projected onto the (u^*, v^*) plane in the case of CIELUV.
4. Using the projected 102 points, perform the Delaunay triangulation operator (using MATLAB®, Qhull, Mathematica®, Maple®, R, or another computational tool) to obtain the “triangulation set” of the projected 102 points on the plane. [5.8] Additionally, the projected white point is added by performing Delaunay triangulation on the projected white point to the six primary and secondary (RGBYMC) projected points.
5. In three dimensional, *e.g.*, CIELAB or CIELUV) space, an inner point is calculated as the average of the 8 points: red, green, blue, yellow, magenta, cyan, black, and white. Tetrahedrons are formed by connecting the triangulation set from step 4 to the inner point. In total, this action will create 192 tetrahedrons. This total is given by 31 tetrahedrons \times 6 areas (red-yellow, yellow-green, green-cyan, cyan-blue, blue-magenta, and magenta-red) + 6 (primary and secondary) colors to white tetrahedrons = 186 + 6 = 192 total. See FIGURE 5.30.

The volume of each tetrahedron is given by:

$$V_N = \frac{1}{6} \left| (\vec{p}_N \times \vec{q}_N) \cdot \vec{r}_N \right|, \text{ where } N = \{1, 2, 3, \dots, 192\} \quad (5.56)$$

6. The color gamut volume is given by the summation of volumes.

$$V_{\text{CRC}} = \sum_N V_N. \quad (5.57)$$

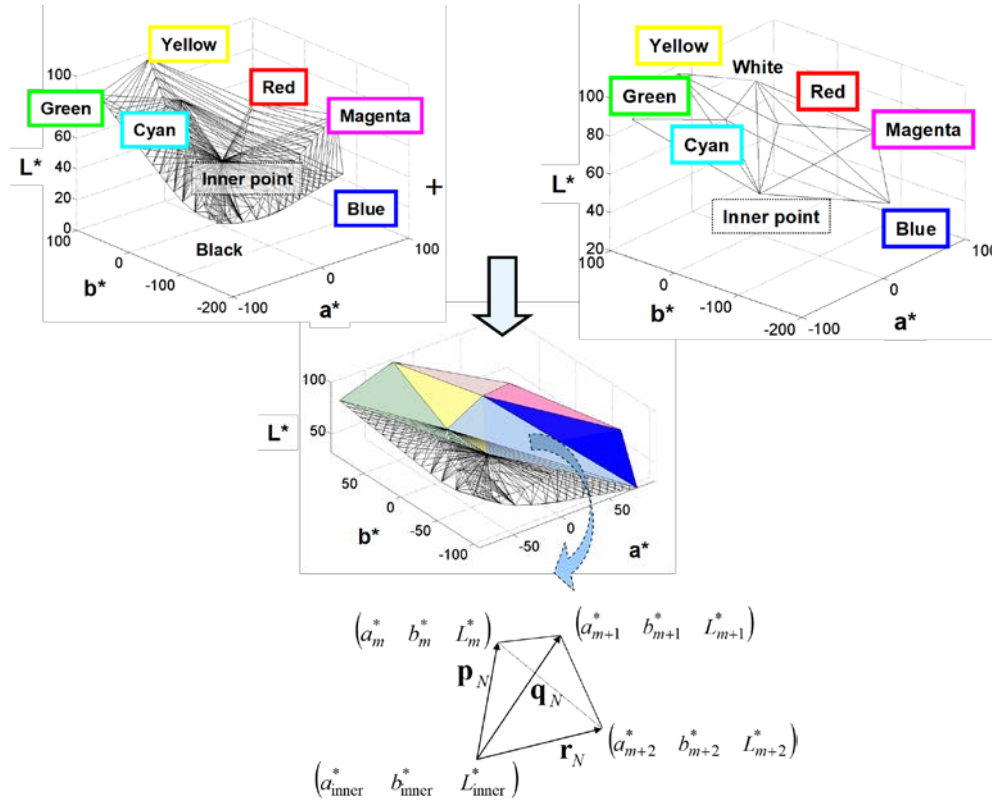


FIGURE 5.30. Triangulations.



REPORTING

The V_{CRC} and the percent of color gamut volume relative to the IEC sRGB standard color space (IEC 61966-2-1) with a D65 white point shall be reported in a form described by the reporting example table.

COMMENTS

1. Because a three-dimensional model such as CIELAB or CIELUV is used, V_{CRC} can only be represented properly in a three-dimensional space, which is based on nonlinearly compressed CIE XYZ color space coordinates.
2. Other Color Spaces: Color spaces like CIELAB and CIELUV where a Euclidean metric is defined and luminance affects the color, such as the Hunt color space, can also be employed. However, in such a case it must be clearly specified in all reporting documentation and be agreeable to all interested parties.
3. The triangulation process can be visualized as in FIGURES 5.30 and 5.31 and the accompanying description.

REFERENCES

- [5.8] F. Aurenhammer, “Voronoi diagrams - A survey of a fundamental geometric data structure”, ACM Computing Surveys Volume 23, Issue 3, pp 345–405. DOI:[10.1145/116873.116880](https://doi.org/10.1145/116873.116880).
- [5.9] C. B. Barber, D. P. Dobkin, and H. T. Huhdanpaa, “The Quickhull Algorithm for Convex Hulls.” ACM Transactions on Mathematical Software, Volume 22, Issue 4, pp 469–483, DOI:[10.1145/235815.235821](https://doi.org/10.1145/235815.235821).

5.32 Color Gamut Envelope—Color Capability

DESCRIPTION

The color gamut of a display can be realized as a 3-dimensional volume, ranging from the display white at the top, outward to its most saturated colors, and then further downward to the display's black point. In this section, that Color Gamut Envelope is measured, analyzed, and a set of useful comparison metrics are derived.

Unit: ΔE^3 . Symbol: None

The first step to realize the Gamut Envelope is to measure the color produced in response to a set of RGB input signal values distributed on the surface of the RGB cube. Those measured colors are then transformed to a perceptually homogeneous device-independent color space. In that color space a geometric hull is created to evaluate the display's color capability (see example in FIGURE 5.32).

Focusing on the surface of the input signal cube allows examination of the system's maximum color range while limiting the total number of color measurements needed. An added advantage to the use of the input signal surface is the ability to pre-determine the geometric tessellation of the hull. This approach greatly simplifies the calculation required for the derived metrics.

The gamut envelope is calculated in the human perceptual color space CIE 1976 D50 $L^*a^*b^*$. This color space has good perceptual homogeneity, which is the most important characteristic for the evaluation and comparison of

TABLE 5.29. Reporting example.

Do not use any values shown to represent expected results of your measurements.

Volume, V_{CRC}	8.20×10^5
Percent relative to sRGB in CIELAB	100 %

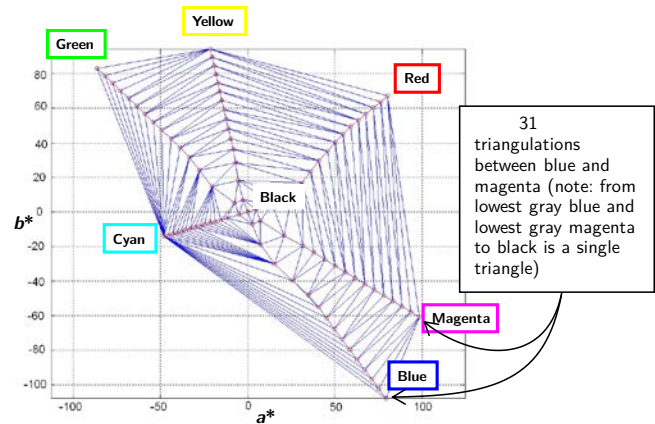


FIGURE 5.31. Between blue and magenta (for example), there are a total of 31 triangulations. Therefore, from black to the 6 (red, green, blue, cyan, magenta, and yellow) points of peak luminance, there are a total of 186 triangulations.



color range and distance. A single common device-independent color space allows disparate display systems to be compared.

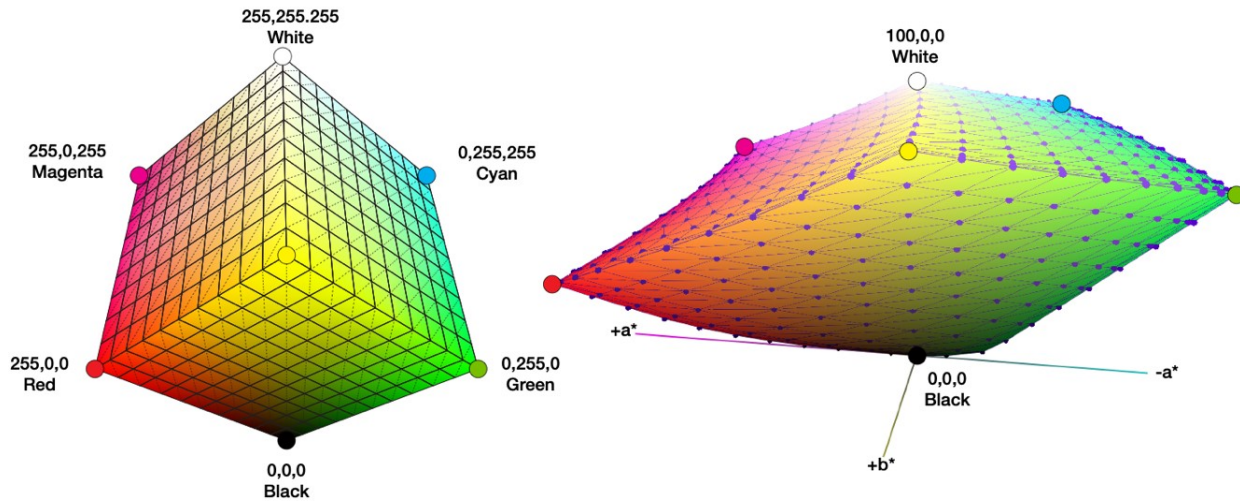


FIGURE 5.32. On the left is the linear unbounded RGB signal space (8 bit) tessellated by 602 evenly distributed points on its surface. On the right is the response of an ideal sRGB display to the 602 test points in the CIE 1976 $L^*a^*b^*$ color space using the same tessellation.

A key component of device independence is chromatic adaptation. The human perception of color is always relative to the perceived illuminant. A display's white point changes how color is perceived. By transforming the measurements to a common illuminant, all displays can be evaluated independently and compared with each other.

To achieve device independence, a chromatic adaptation transform matrix is calculated from the white point of the DUT to the common illuminant of the device independent color space. This matrix is used to transform all the measured color values of the DUT into the device independent color space. This preserves the perceived color distances regardless of the actual display white point.

The device independent color space and the chromatic adaptation used in this method is identical to that specified by the International Color Consortium (ICC). This method is therefore compatible with color volume and color distances calculated by all the major computer operating systems and all software for visual media content creation on those systems. This method has also been shown to arrive at accurate color volumes for reference color spaces and real displays within the stated uncertainty that match the laborious 4913 measurement points in the CIE 168 method.

For the purposes of this document, the final ordered dataset of 602 colors in the CIE 1976 D50 $L^*a^*b^*$ color space is called the display's "Color Gamut Envelope".

While other methodologies may be used to measure and calculate the Color Gamut Envelope, this approach focuses on a single reference method. If the behavior of a particular display system is understood and well modeled, fewer measurements combined with interpolation and/or a mathematical model may be used to determine the 602-point dataset. Any such alternative methodology should be first proved to arrive at the same CIELAB Gamut Volume (CGV) result within the uncertainty of the CGV metric in 5.32.1.

SETUP

As defined by these icons, standard setup details apply (3.2):



Use the pattern (CAPL-25) shown in FIGURE 5.33 to measure the response to the input signal values. This pattern has dynamic components to compensate for total signal loading. The center patch is changed to the test value and the compensation patches are set to the inverse RGB value $(1 - R, 1 - G, 1 - B)$. If the display under test has no significant variation with signal loading a static version of the target which replaces the dynamic component with a middle gray $(0.5R, 0.5G, 0.5B)$ may be used.

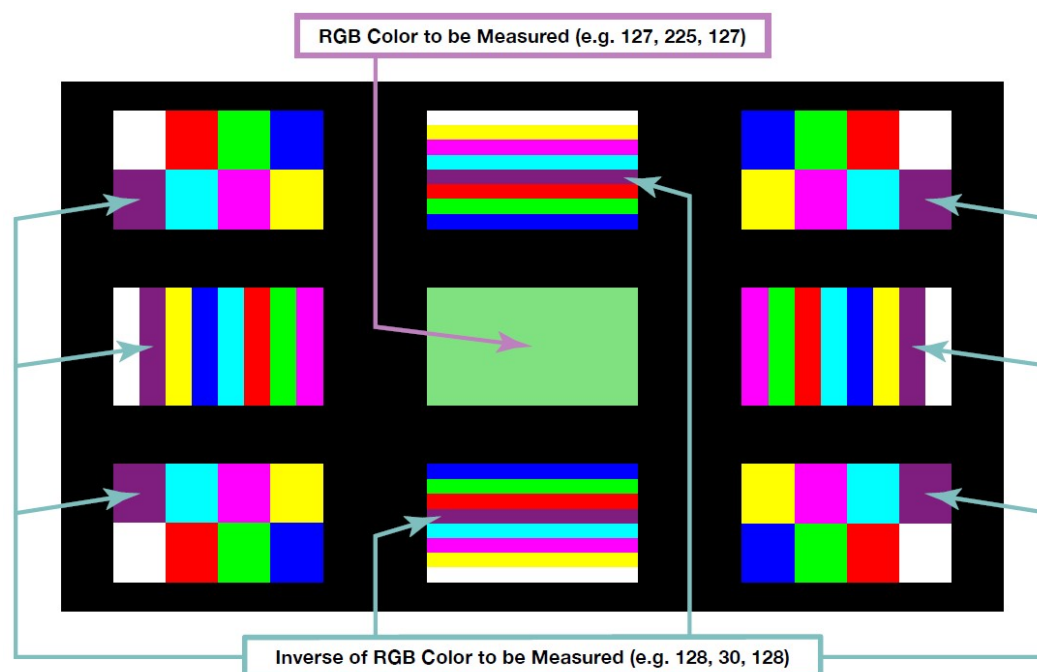


FIGURE 5.33. CAPL-25 Test Pattern with an example test color and its inverse. The callouts indicate the test color and the placement of the inverse dynamic components.

Caution: Due to the total flux of the test target, it will likely be necessary to employ a mask to prevent stray light from entering the LMD — See IDMS Appendix A – 2.1.5 Stray-Light-Elimination Tubes (SLETs) for details. The SLET should be used for all the measurements, not just for the darker measurements.

REFERENCE METHOD

The reference method comprises three functional steps:

1. Measuring the tristimulus values (CIE 1931 X, Y, Z) displayed for the reference color set comprising 602 ordered input signal values. This pre-defined ordered set consists of an evenly spaced 11×11 grid on each face of the RGB signal cube.
2. Using the prescribed chromatic adaptation transform (CAT) to convert the measured tristimulus values to the standard illuminant D50 and then to the device-independent color space CIE 1976 $L^*a^*b^*$.
3. Recording the resulting color list to the specified ASCII data format for further software interpretation and analysis. The format used is derived from the CGATS 17 Format 2 Color Data Standard.

The reference method uses a predefined set of 602 colors on the surface of the gamut solid that provides adequate coverage to create an accurate estimate of the gamut envelope. This number of color measurements is required to



achieve the uncertainty values of the metrics described in this section. This corresponds to an 11×11 grid on each face of the RGB signal cube.

Smaller measurement sets can be used to make estimates with greater uncertainty. If the display gamut surface is smooth with largely flat faces, fewer points may provide a fairly accurate estimate. The example code will also generate color signal values and analyze datasets for 5×5 , 7×7 and 9×9 grids on each face. The code will perform linear interpolation in the CIE 1931 XYZ color space to generate the 602-color set. Always report such results as an estimate with the number of sampled points and unknown uncertainty if less than the full set is used.

If the behavior of the DUT is not known, the full 602-color reference set should always be used. If the color mixing behavior of the DUT is well understood and modeled, a smaller color set could be used as an input to the model which would create the 602-color set. Tests should be performed to assure that the model used is accurate to the reference method (for example, by validating the results against the full 602-color reference set).

The spacing of the signal values in the reference set are optimized for conventional signal encodings. They will function well and within the uncertainty for display EOTFs approximating anything from a linear response to Gamma 4.0. Signal encodings with extreme EOTFs or luminance encoded values would require different spacing of the input signal colors in order to achieve a perceptually more even distribution over the gamut surface. It is important to note that if the signal spacing is perceptually optimized for an individual display encoding, the reference software will still correctly build the metrics in this section as long as the tessellation order of the surface is maintained.

The reference color set is derived from the surface of the RGB input signal. An RGB input signal is essentially a cube with 8 corners of the colors K=black, R=red, G=green, B=blue, C=cyan, M=magenta, Y=yellow, and W=white resulting in 12 edge vectors. Each edge vector is divided into 10 rays resulting in $m = 11$ points. Each face of the cube (the region between four connected edge vectors) is thus divided into a grid. For the reference set, this results in 602 unique colors to measure:

$$n = 6m^2 - 12m + 8 \quad (5.58)$$

See Code 1 below under Reference Software Code for a sample program that will select the required RGB signal values based upon the number of edge divisions m and the bit depth of your input signal.

PROCEDURE

Determine the tristimulus values of the selected colors:

1. Determine the RGB signal values of the gamut surface points to be measured. Use the program in Code 1 to calculate the reference set with $m=11$ for normal EOTFs. Each color Q_i is identified by
2. $Q_i = (R_i, G_i, B_i), i = 1, 2, 3, \dots, 6m^2 - 12m + 8$ (5.59)
3. Measure the tristimulus values (X_i, Y_i, Z_i) of each color Q_i .

ANALYSIS

Build a chromatic adaptation transform (CAT) to adapt the measured values from the display white point (X_W, Y_W, Z_W) to the standard illuminant D50 $(X_{D50}, Y_{D50}, Z_{D50})$ using the modified Bradford adaptation transform method in the following equation.

$$\begin{bmatrix} X_i' \\ Y_i' \\ Z_i' \end{bmatrix} = \mathbf{M}_B^{-1} \cdot \mathbf{A} \cdot \mathbf{M}_B \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} \quad (5.60)$$

where the -1 refers to the inverse matrix, and the Bradford coefficients in matrix \mathbf{M}_B are:



$$\mathbf{M}_B = \begin{bmatrix} 0.8951 & 0.2664 & -0.1614 \\ -0.7502 & 1.7135 & 0.0367 \\ 0.0389 & -0.0685 & 1.0296 \end{bmatrix} \text{ and } \mathbf{A} = \begin{bmatrix} \mathcal{L}'_W \mathcal{L}_{D50}^{-1} & 0 & 0 \\ 0 & \mathcal{M}'_W \mathcal{M}_{D50}^{-1} & 0 \\ 0 & 0 & \mathcal{S}'_W \mathcal{S}_{D50}^{-1} \end{bmatrix} \quad (5.61)$$

with

$$\begin{bmatrix} \mathcal{L}'_W \\ \mathcal{M}'_W \\ \mathcal{S}'_W \end{bmatrix} = \mathbf{M}_B \begin{bmatrix} X'_W \\ Y'_W \\ Z'_W \end{bmatrix} \text{ and } \begin{bmatrix} \mathcal{L}_{D50} \\ \mathcal{M}_{D50} \\ \mathcal{S}_{D50} \end{bmatrix} = \mathbf{M}_B \begin{bmatrix} X_{D50} \\ Y_{D50} \\ Z_{D50} \end{bmatrix} \quad (5.62)$$

Using this CAT convert all the measured tristimulus values (X_i, Y_i, Z_i) relative to the D50 standard illuminant.

Caution: If a subset of the reference 602 test colors is measured, then linear or advanced model interpolation to the full 602 test color set should be performed in the X_i, Y_i, Z_i color space before conversion to CIE $L^*a^*b^*$. All analysis after this point should be performed using the complete 602 color measurement set.

The final results in CIE 1976 D50 $L^*a^*b^*$ coordinates (L_i^*, a_i^*, b_i^*) are then calculated by

$$(X'_{D50}, Y'_{D50}, Z'_{D50}) = \frac{(96.42, 100.00, 82.49)}{100} \quad (5.63)$$

$$L_i^* = 116f\left(\frac{Y'_i}{Y'_{D50}}\right) - 16 \quad (5.64)$$

$$a_i^* = 500 \left[f\left(\frac{X'_i}{X'_{D50}}\right) - f\left(\frac{Y'_i}{Y'_{D50}}\right) \right] \quad (5.65)$$

$$b_i^* = 200 \left[f\left(\frac{Y'_i}{Y'_{D50}}\right) - f\left(\frac{Z'_i}{Z'_{D50}}\right) \right] \quad (5.66)$$

$$f(q) = \begin{cases} q^{\frac{1}{3}}, & \text{if } q > \left(\frac{6}{29}\right)^3 \\ \frac{841}{108}q + \frac{4}{29}, & \text{if } q \leq \left(\frac{6}{29}\right)^3 \end{cases} \quad (5.67)$$

The known structure of the test points on the surface of the RGB input signal cube allows their simple tessellation into a 3D hull in CIE $L^*a^*b^*$ color space. The program in Code 2 will perform the chromatic adaptation, transform the measurements to CIE $L^*a^*b^*$ values, and record the data file in the CGATS 17 color data format. This data file is the DUT's "gamut envelope" and will be used to calculate the metrics in 5.32.1, 5.32.2, and 5.32.3. The gamut envelope can be simply visualized in 3D by performing the original fixed tessellation and plotting the result (see example in FIGURE 5.34.)

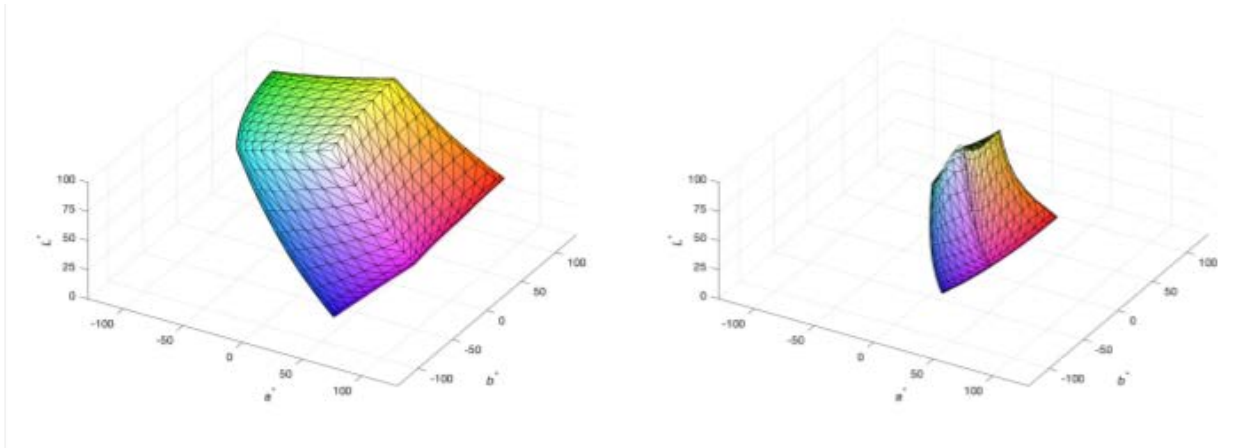


FIGURE 5.34. Two examples of display gamut envelopes created from 602 measured surface colors.

REFERENCE SOFTWARE CODE:

The following program code is written in the commercial MATLAB® language and has also been fully tested running on the open-source [Octave](#) interpreter. The reference software code may be obtained at DOI: [10.55410/bjxb8678](https://doi.org/10.55410/bjxb8678).

Code 1: `make_rgb_signals.m`

This is a sample program to calculate the input signal values for the reference set of 602 colors comprising a linear 11×11 grid on each face of the input signal RGB cube. This program can generate other size input sets such as 7×7 or 9×9 .

Code 2: `Reference_sRGB_IEC_61966-2.1_Synthetic_XYZ_surface10.txt`

This is a sample measurement data file in the CGATS 17 color data format 2. This file has the X, Y, Z values of a perfect sRGB display. Note: These synthetic XYZ values have been normalized to $Y = 1$ for white, but real measurement data do not require normalization.

Code 3: `xyz2lab.m`, `readCGATS.m`, `camcat_cc.m`, `get_d_C.m`, `intersect_d-Cs.m`, `make_tessellation.m`, `map_rows.m`, `writeCGATS.m`. These are common sub-routines required by the code in this section (5.32).

Code 4: `make_gamut_envelope.m`

This is a program to calculate the color gamut envelope and store it as a device-independent standard gamut envelope file using the CGATS 17 color data format 2.

Code 5: File: `Reference_sRGB_IEC_61966-2.1_gamut_envelope.txt`

This is a sample color gamut envelope file in the CGATS 17 color data format 2. This file has the CIE 1976 $L^*a^*b^*$ D50 values of a perfect sRGB display. It is the result of running Code 4 on the data in Code 2.

5.32.1 CIELAB gamut volume

ALIAS

color gamut volume, gamut volume

DESCRIPTION

CIELAB gamut volume (CGV) provides a single unit value that describes the size of a display's color gamut. CGV is calculated by geometrically measuring the volume of the color gamut envelope. CGV is a useful metric towards



understanding the color capability of a display. While CGV provides an accurate and device independent measurement for the overall size of the display color gamut, it does not provide information about where that range of color exists in color space. The gamut envelope metrics in section 5.32.2 CIELAB Gamut Intersection and 5.32.3 CIELAB Gamut Ring Diagram provide this further color capability information.

SETUP

None. This analysis is based upon the data obtained in 5.32.

Other setup conditions: None

ANALYSIS

Many methods exist for calculating the volume of complex polyhedra. The reference method implemented in this section uses an approach that both simplifies the calculation and leads directly to the further analysis and methods contained in this section.

An intermediary form of the $L^*a^*b^*$ gamut envelope is built by considering the cylindrical coordinates of lightness L^* , hue h^* , and chroma C^* . A grid of vectors is considered emanating from the L^* -axis and uniformly spaced in L^* and h^* , typically using a step ΔL^* of 1 and a step Δh^* of 1° . For each ray, the Möller-Trumbore [5.10] ray-triangle intersection algorithm is used to identify the N points of intersection of this vector with the gamut surface yielding chroma values $C^*(L^*, h^*, n)$ for $n = 1 \dots N$. For each point the surface orientation $d(L^*, h^*, n)$ is also calculated as the sign of the dot-product of the vector and the outward surface normal of the intersected tile. The volume contribution for each L^*, h^* of the gamut, and the total volume, can then be calculated as:

$$V(L^*, h^*) = \frac{\Delta L^* \Delta h^*}{2} \sum_n d(L^*, h^*, n) C^*(L^*, h^*, n)^2 \quad (5.68)$$

and

$$V_{\text{total}} = \sum_{L^* h^*} V(L^*, h^*) \quad (5.69)$$

Some example CGV calculations for several color gamut envelopes are illustrated in FIGURE 5.35.

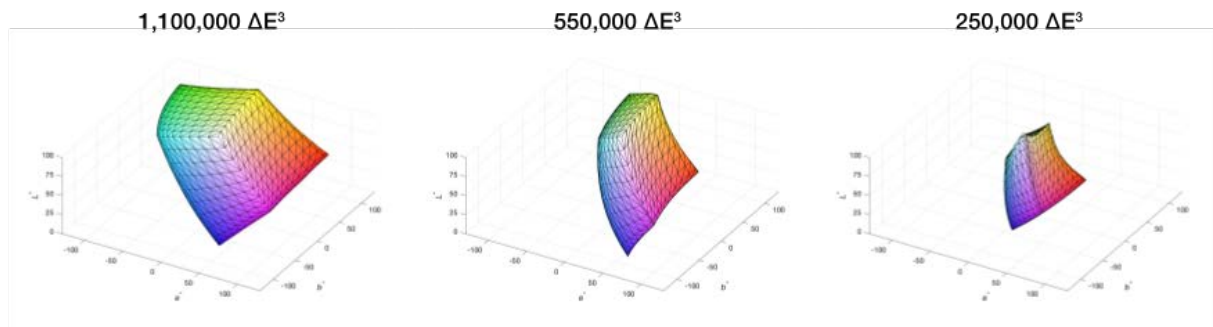


FIGURE 5.35. Three example real measured display Gamut Envelopes plotted in CIE $L^*a^*b^*$ with their corresponding color gamut volume in ΔE^3 . While plotting the gamut envelope in 3D can be useful it can also be quite misleading. The distortions introduced by 3D perspective and the portions hidden from view make comparisons difficult. The gamut volume metric provides a clear unambiguous indication of relative size.

REPORTING

1. Report the number of colors measured to create the gamut envelope of the DUT. This is optional if the full 602 sample set is used.

Example: gamut envelope color samples = 602



2. Report the gamut volume of the DUT in ΔE^3

Example: CGV=810,000 ΔE^3 or $8.1 \times 10^5 \Delta E^3$

3. Due to the complexity of the gamut envelope measurement, CGV should only be reported with two significant digits up to CGV = 10^6 and 3 significant digits thereafter, *e.g.*, 96,000, 830,000, and 1,230,000, or equivalently, 9.6×10^4 , 8.3×10^5 , and 1.23×10^6 .

SOFTWARE CODE

Code 6: `get_volume.m`

This is a sample program that takes as input the standard gamut envelope file generated by Code 4 in 5.32 and returns the CIELAB gamut volume in ΔE^3 .

REFERENCE

- [5.10] Tomas Möller (1997) A Fast Triangle-Triangle Intersection Test, Journal of Graphics Tools, 2:2, 25-30, DOI: [10.1080/10867651.1997.10487472](https://doi.org/10.1080/10867651.1997.10487472)

5.32.2 CIELAB Gamut Intersection

ALIAS

reference intersection, gamut coverage

DESCRIPTION

CIELAB gamut intersection is the volume of the binary intersection between the gamut envelope of a reference color space and the color gamut envelope of the DUT.

It is often important to know how well a display covers the gamut of a reference color space. For example, if content mastered in the sRGB color space will be sent to a display, it would be desirable to understand how capable that display is of reproducing the colors in that content.

The sRGB color space has a CIELAB gamut volume of 830,000 ΔE^3 . A display under evaluation may have a measured CIELAB gamut volume of 900,000 ΔE^3 . However, this larger volume does not ensure that the display can reproduce all the colors of sRGB. That larger volume may not completely overlap the sRGB color space. The goal of this metric is to quantify how much of a reference color space is actually covered by the DUT's CIELAB Gamut Envelope. The geometric intersection of the two color gamut envelopes provides this information. This intersection can be described both as an actual Volume in ΔE^3 or as a percentage of coverage. An example of the complex relationship between an actual display and a reference color space can be seen in FIGURE 5.36.

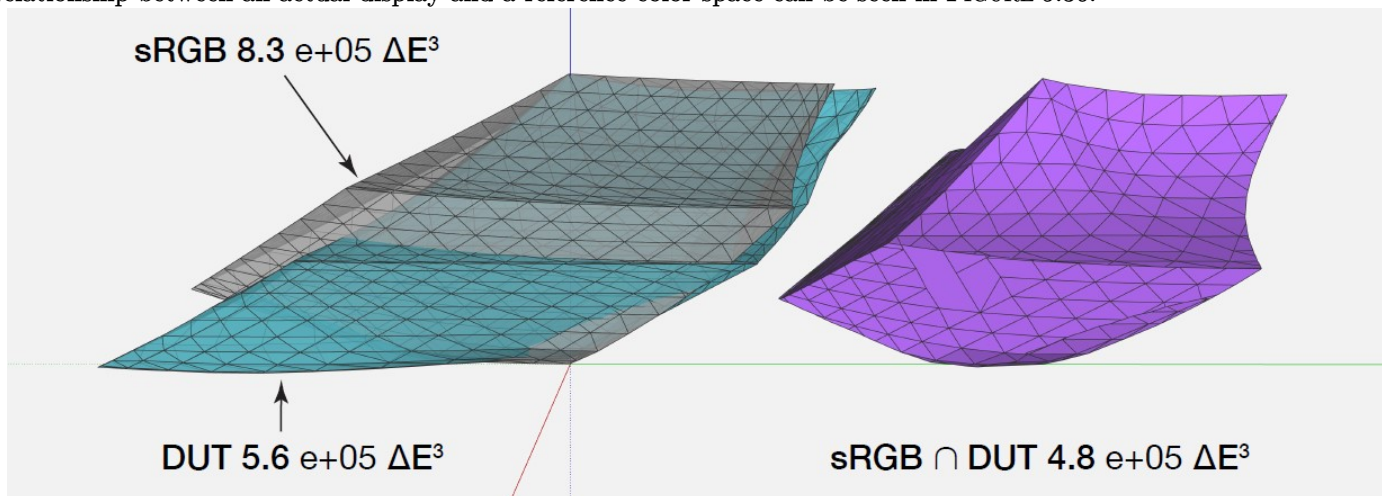




FIGURE 5.36. A measured display gamut envelope superimposed with the sRGB reference gamut envelope. Regions of the display color space exist outside the reference space. Regions of the reference color space are not fully covered by the display. The CIELAB gamut intersection shown in purple is the binary intersection of the two gamut envelopes and indicates the proportion of the reference gamut the display is capable of reproducing. In this example the display covers 58% of sRGB.

SETUP

None. This analysis is based upon the data obtained in previous sections.

ANALYSIS

There are a number of known geometrical methods which could be used to calculate the binary intersection of two gamut envelopes expressed as complex polyhedral, however they are typically algorithmically complex and difficult to implement. The reference code provided in this section leverages the intermediate form of CIE $L^*a^*b^*$ ($L^*h^*C^*$) used in the volume calculation. This reduces the problem from a 3D intersection to a much simpler 1D intersection performed on each set of intersections found for each (L^*, h^*) vector.

Consider the set of intersections for two different gamut volumes at a particular (L^*, h^*) in descending order of C^* , and an initially empty list of C^* and surface orientation d values for the intersected volume. Each positive surface orientation d indicates entering the respective gamut volume at the respective C^* and each negative d indicates an exit. A C^* value and a positive d is only added to the intersected gamut list once a positive intersection has been passed for both source gamuts. Once a positive orientation d is added, a negative orientation d and corresponding C^* is added once a negatively oriented surface is passed for either of the source gamuts. Performing this algorithm for every L^* and h^* results in an intersected $C^*(L^*, h^*, n)$ and $d(L^*, h^*, n)$ which can then be used for intersected volume.

REPORTING

1. Report the number of colors measured to create the gamut envelope of the DUT.
2. Report the reference color space used, *e.g.*, sRGB_IEC_61966-2.1.)
3. Report both the color gamut volume in ΔE^3 of the reference color space and the color gamut volume in ΔE^3 of the DUT.
4. Report the volume of the gamut envelope intersection of the DUT and the reference color space

Example: $|\text{sRGB} \cap \text{DUT}| = 800,000 \Delta E^3$

Due to the complexity of the gamut envelope measurement, gamut intersection should only be reported with 2 significant digits up to $\text{CGV} = 10^6$ and 3 significant digits thereafter, *e.g.*, 96,000, 830,000, and 1,230,000, or equivalently, 9.6×10^4 , 8.3×10^5 , and 1.23×10^6 .

5. Optionally report the coverage (%CGVC) for the DUT relative to the reference color space in whole numbers (this number should never exceed 100%). This number will be

$$\% \text{CGVC} = \frac{|\text{REF}_{\text{gamut env}} \cap \text{DUT}_{\text{gamut env}}|}{\Delta E_{\text{REF}}^3} \times 100$$

Example: %CGVC = 96% of sRGB

SOFTWARE CODE

Code 7: `get_intersection_volume.m`

This is a reference program that takes two standard gamut envelope files as input and returns the color gamut volume of their binary intersection in ΔE^3 .



5.32.3 CIELAB Gamut Ring Diagram

ALIAS

gamut rings, ring diagram

DESCRIPTION

The gamut ring diagram is a two-dimensional visualization of the color gamut envelope that clearly communicates both the range and composition of the DUT's color capability without visual distortion. The gamut ring diagram has a direct 1:1 correlation between the 2D area and the 3D color gamut volume, providing an unambiguous evaluation of a display's color capability (see FIGURE 5.37). The gamut ring diagram illustrates the volume of the color gamut envelope by hue vector in each of 10 Lightness (L^*) slices, indicating where in the color gamut deficiencies or strengths exist. The ring diagram can also be drawn to include the outside boundary of a reference color space, in this way it illustrates the color regions that are deficient or exceed the reference (see FIGURE 5.38).

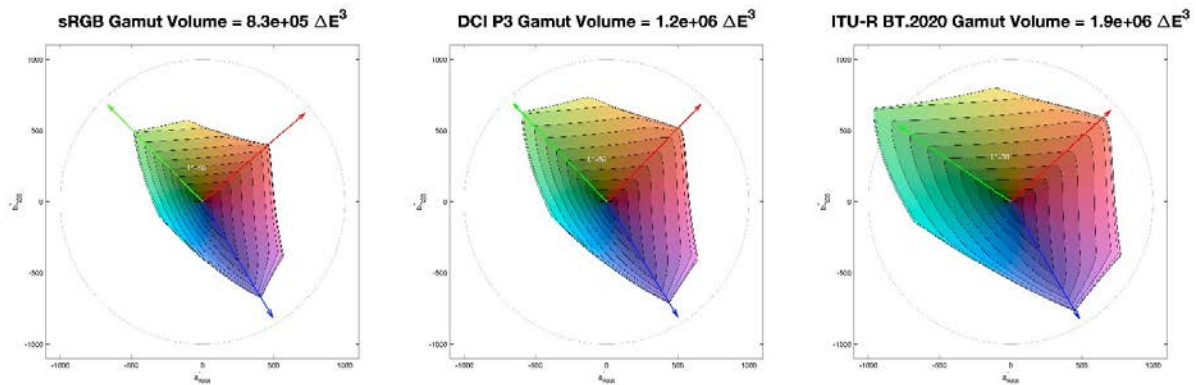


FIGURE 5.37. Simple gamut ring diagrams of three standard reference display color spaces. It is important to always plot the diagram as a square with an axis range of -1100 to $+1100$ for a_{RSS}^* and b_{RSS}^* . The relative size compared to this box and the chroma ring at 1000 provide crucial visual cues to the scale of the color gamut volume. These plots also include the signal primary hue vectors. This is the measured hue angle for the pure R_{max} , G_{max} , and B_{max} signal.

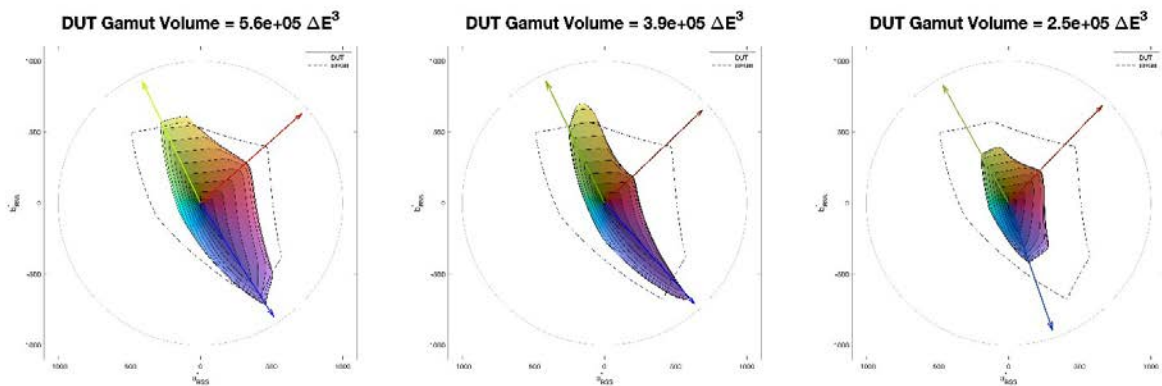


FIGURE 5.38. Three real measured display Gamut Envelopes are visualized using the Gamut Ring Diagram along with their Gamut Volume. While Gamut Volume provides information about size, the Gamut Rings also reveal where in hue space the gamut volume exists. In these examples the sRGB gamut envelope boundary has been plotted as an outline to reveal the relative volume of the display compared to the sRGB standard in each hue direction.



The gamut ring diagram is comprised of 10 concentric rings plotted on two axes, a_{RSS}^* and b_{RSS}^* . Each ring outward from the center represents slices of the CIELAB gamut volume in $10L^*$ steps. The innermost ring represents the volume of the $0 - 10L^*$ slice of the CIELAB gamut envelope. The next ring outward represents the slice from $10 - 20L^*$... ultimately the last ring represents the slice from $90 - 100L^*$. The width of the ring along any hue vector represents the volume along that hue vector in that slice (see .FIGURE 5.39)

SETUP

None. This analysis is based upon the data obtained in previous sections.

Other setup conditions: None

ANALYSIS

The reference implementation begins with the same efficient gamut volume calculation described in 5.32.1 to estimate $V(L^*, h^*)$. To determine the gamut rings from this data, the root sum square of the chroma values is first calculated at each hue angle h^* in the lightness range 0 to L^* with hue step Δh^* using the following formula:

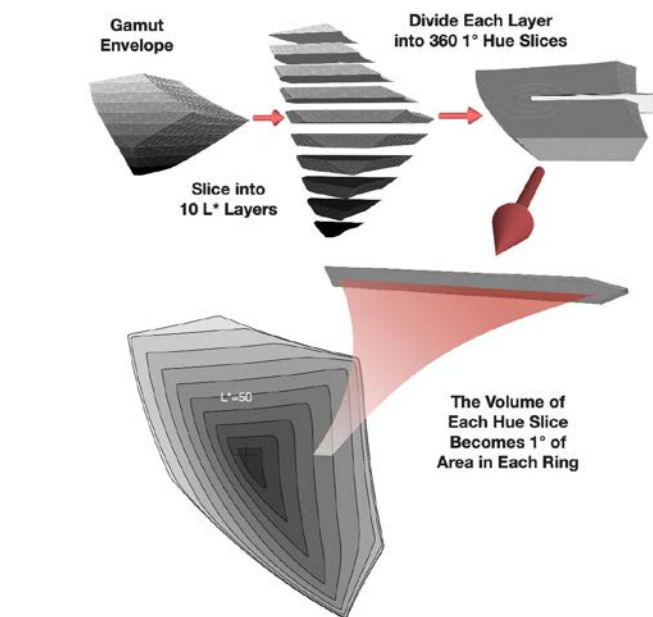


FIGURE 5.39. A functional representation of the transformation from gamut envelope to gamut ring diagram. Demonstrating how the volume of each 1° hue slice out of each $10L^*$ layer becomes an area in each $10L^*$ ring.

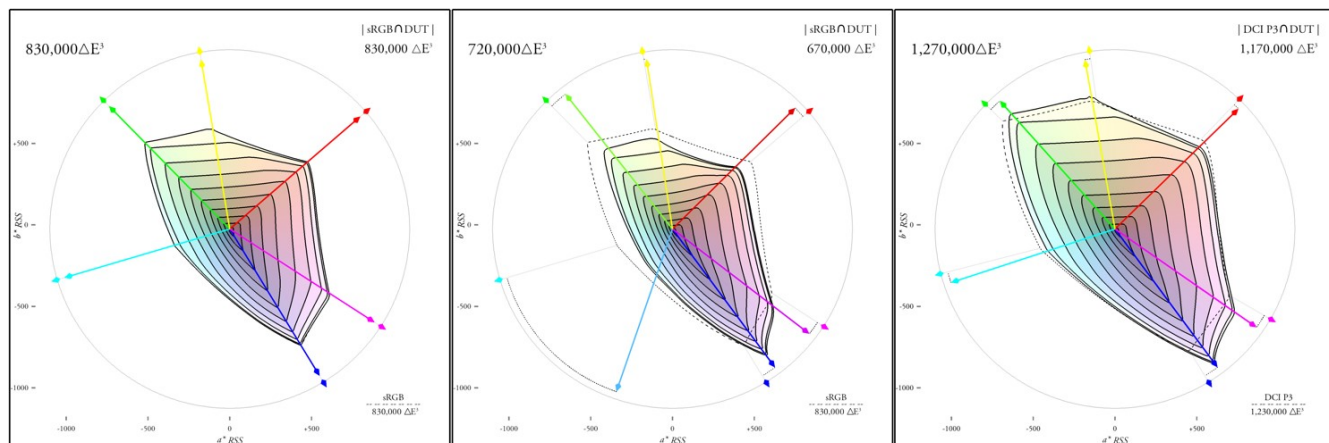


FIGURE 5.40. Three examples of complete gamut envelope analysis with all optional reporting. In the panel to the left is an example of unity, a perfect sRGB display plotted with sRGB as the reference. In the center panel the DUT has some deficiencies relative to the sRGB standard. In particular, there is a significant hue error in the cyan vector. Note also the $720,000 \Delta E^3$ volume that only intersects $670,000 \Delta E^3$ of sRGB. The panel to the right is a much wider gamut display plotted against the DCI P3 reference color space. These diagrams still have all 10 rings from 0 to $100L^*$, the colormap of the diagram has simply been lightened to increase clarity. The ring diagram can be plotted with no color fill at all or in grayscale.



$$C_{\text{RSS}}^*(L^*, h^*) = \sqrt{\frac{2}{\Delta h^*} \sum_{L_j^*=0}^{L_j^*=L^*} V(L_j^*, h^*)} \quad (5.70)$$

The $(a_{\text{RSS}}^*, b_{\text{RSS}}^*)_{L^*, h^*}$ coordinates of C_{RSS}^* at a hue angle h^* in the lightness range from 0 to L^* are defined as:

$$(a_{\text{RSS}}^*, b_{\text{RSS}}^*)_{L^*, h^*} = C_{\text{RSS}}^*(L^*, h^*)(\cos h^*, \sin h^*) \quad (5.71)$$

Plot the $a_{\text{RSS}}^*, b_{\text{RSS}}^*$ data as a set of rings, one ring for each L^* value.

REPORTING

1. Report the number of colors measured to create the color gamut envelope of the DUT.
2. Report the plot of the gamut ring diagram. Assure the unit distance of the a_{RSS}^* and b_{RSS}^* axes are identical. Do not distort the diagram through non-uniform scaling.
3. Optional – Report the gamut volume of the DUT
4. Optional – Plot a reference gamut envelope boundary (10th ring of reference color gamut ring) on the plot for comparison, report the reference color space used, *e.g.*, sRGB_IEC_61966-2.1.
5. Optional – Report the CIELAB gamut intersection with the reference color gamut envelope.
6. Optional – Plot the hue vectors for the measured signal primary colors, that is red at (255,0,0), green at (0, 255, 0), and blue at (0, 0, 255) using 8-bit encoding.
7. Optional – Plot the hue vectors for the measured signal secondary colors, that is cyan at (0, 255, 255), Magenta at (255, 0, 255), and Yellow (255, 255, 0) using 8-bit encoding.
8. Optional – Plot the target hue vectors for the reference color gamut envelope and optionally indicate the Δh arc.

REFERENCE CODE

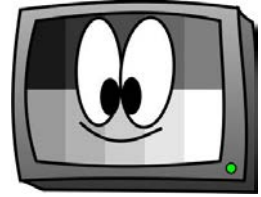
Code 8: `plot_rings.m`

This is a reference program that takes as input a standard color gamut envelope file and plots the corresponding gamut ring diagram in $(a_{\text{RSS}}^*, b_{\text{RSS}}^*)$ coordinate space. While the math used in the reference code is slightly different from the math shown above, the relationships are identical.



6. GRAY- & COLOR-SCALE MEASUREMENTS

A number of measurement methods to characterize the grayscale and color scales of a display are very similar except for the pattern used, the placement of the detector, or the calculation made. Here we measure the gray scale (relationship between the stimulus gray level and the resulting gray shade), and the color scales of a display. A spreadsheet for plotting and calculating results for nine levels is available at <https://doi.org/10.55410/ikfp2784>. It also has details for creating other numbers of levels. We use the term “gamma” to refer to the simple model found in § 6.3 Log-Log Gamma Determination. Strictly speaking, we might always place the word “gamma” in quotation marks to remind the user that it is a sloppy notation and that we are not referring to the gamma function. However, most users are comfortable with the use of the word and such a ritual will not be maintained.



The examples provided are not anticipated values, as is true throughout the rest of this document. However, because of rounding and using only three significant figures in showing these values, some of the calculations discussed will not produce exactly the same numbers if you use the numbers provided in the examples. To follow the calculations precisely, please refer to the spreadsheet Gray-and-Color-Scales.xls supplied with the printed copy of this document.

NINE LEVEL, ETC., SCALE DIVISION—HARMONIZED GRAY SCALES: We would like to introduce the 9-level, 17-level, and 33-level gray and color scales. Many give much attention to 8, 16, and 32 levels. However, the new 9, 17, 33, etc. level scales have some very nice properties such as more uniform and consistent division of the gray level range. For the harmonization obtained with the 9, 17, 33, ... levels and for the selection of subsets of a gray scale, full details are supplied in the appendix, § A12.1.1 Rendering Gray and Color Levels. The table illustrates the uniformity of the nine-level vs. the eight-level division of the gray scale based upon the following mathematics.

DIGITAL GRAY SCALES: As provided in the appendix, here is a specification for how to select a subset of M levels from a set of N available levels:

N is the number of available gray or color levels. For example, with an eight-bit scale, $N = 2^8 = 256$. For a ten-bit display, there are 1024 levels, and for a 12-bit display, there are 4096 levels.

$n = 1, 2, \dots, N$ is an *index* for a particular gray or color-primary level for the full gray scale or color scale. Level $n = N$ refers to white or a fully-on primary color, and level $n = 1$ refers to black.

Thus, $L_1 = L_K$ is black, and $L_N = L_W$ is white.

$w = N - 1$ is the bit level or command level associated with white or a maximum color primary; for the eight-bit scale, $w = 255$. The black bit level is 0.

M is the number of levels extracted from the complete set of N levels. We will often use 9, 17, 33, etc. levels (in the past we often used 8, 16, and 32 levels).

$j = 1, 2, \dots, M$ is the *index* for the extracted levels, the level number such as level 1, level 6, etc.

ΔV is the average spacing between extracted levels: $\Delta V = (N - 1)/(M - 1) = w/(M - 1)$ and may not be an integer.

$V_j = \text{int}[(j - 1) \Delta V] = 0, \text{int}(\Delta V), \text{int}(2\Delta V), \dots, w$ are the bit levels used for the extracted M levels. For an eight-bit display $V_M = 255 = w$ for white or fully-on color primary and $V_K = V_1 = 0$ for black.

$\Delta V_j = V_j - V_{j-1}$, $j = 2, 3, \dots, M$, is the spacing between the extracted levels and will not be the same for all the m , in general.

To summarize:

Black: $V_1 \equiv V_K \equiv 0$ (= 0 usually, for 8-bit displays) produces black

$L_1 \equiv L_K$.

White: $V_M \equiv V_W \equiv w$ (= 255 for 8-bit displays) produces white $L_M \equiv L_W$.

ANALOG SIGNAL LEVELS: For analog signals, if V_W is the white or fully-on color primary signal level and V_K is the black signal level, then for M evenly spaced levels the signal step size is $\Delta V = (V_W - V_K)/M$ and the selected signal levels are $V_j = V_K + (j - 1)\Delta V$, for $j = 1, 2, \dots, M$.

Level index, j	$M = 9$		
	Gray level, V_j	Level difference, ΔV_j	Binary code
1	0		00000000
2	31	31	00011111
3	63	32	00111111
4	95	32	01011111
5	127	32	01111111
6	159	32	10011111
7	191	32	10111111
8	223	32	11011111
9	255	32	11111111



TEST PATTERNS FOR VARIOUS TECHNOLOGIES: Different test patterns can be used for different display technologies, especially those that can adjust their gray levels dynamically based upon the image content.

FULL-SCREEN PATTERNS: For many display technologies, the full screen test patterns can be used for gray-scale measurements as shown in Fig. 1. This test pattern is used whenever the full-screen white luminance is preserved independent of the size of the white region (no power loading is observed).

BOX PATTERNS: In the case of technologies that are not able to achieve the full gray level range for full-screen patterns due to power loading, a smaller measurement area such as boxed pattern shown in Fig. 2 is recommended.

FIXED AVERAGE-PIXEL-LEVEL (APL) PATTERNS: The patterns in Figs. 3-5 are suggested for display technologies that dynamically adjust gray levels based on image content such as global and local dimming displays. The numbers shown in Fig. 3 stand for the gray level of that rectangular patch. Attempts are made to maintain a constant APL with the patterns in Figs. 3 and 5; the patches are cycled through the center where the measurement is made—see Figs. 6 and 7, where it shows the beginning of the sequences (A13.2 Setup Targets in Pattern Collections). As an alternative, the test pattern in Fig. 5 could be also used for arbitrary grey levels, where the surround luminance L_S is adjusted for each gray shade luminance L_X measured at the center to maintain an APL or display luminance. For displays that adjust gray levels dynamically based on predicted power, picture, or luminance level, the relationship between picture level and power or luminance would also have to be understood, because it may change depending upon the pattern used. In some cases, it may be best to turn off the local or global dimming feature in order to measure the gray scale of the display. Thus, selecting the appropriate test pattern is not a trivial task.

One way to implement the pattern in Fig. 5

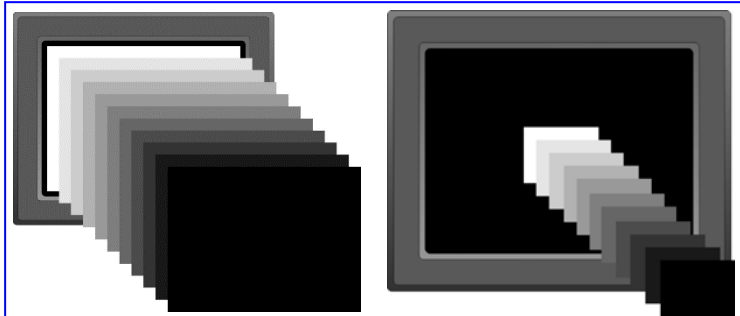


Fig. 1. Full-screen pattern.



Fig. 2. Box pattern.

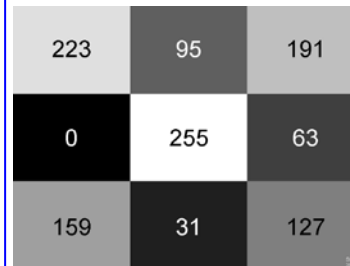


Fig. 3. SCPL# patterns.



Fig. 4. SCPL## patterns.

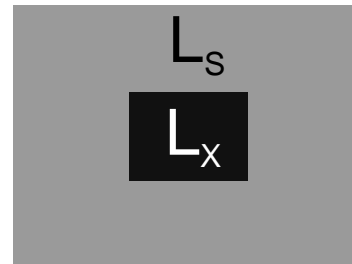


Fig. 5. APL box patterns.

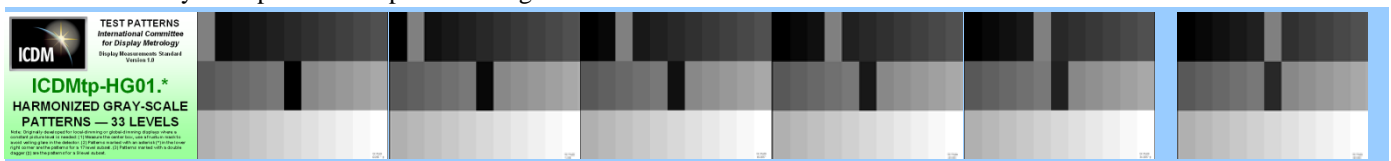


Fig. 6. Beginning sequence of snaking constant-pixel-level patterns in ICDMtp-HG01.* containing 33 gray levels.

is to make it area proportional by requiring $L_S = (L_{APL} - L_X A_X) / (A - A_X)$, where L_{APL} is the selected APL luminance average for the entire screen, A is the screen area, and A_X is the area of the patch. Another way is to make the background L_S is from level $V_S = \text{int}[0.5(0.7V_X + 0.3N)]$ where V_X = patch command level for L_X , N = total number of command levels [see Softcopy Exploitation Display Hardware Performance Standard Version 2.1, 28 August 2006, National-Geospatial Intelligence Agency (NGA) Image Quality and Utility (IQ&U) Program].

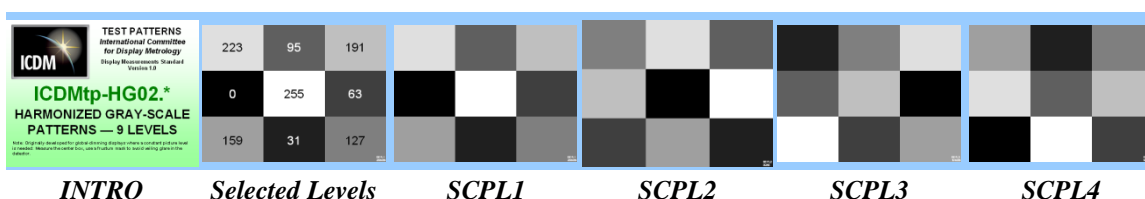


Fig. 7. Beginning sequence of snaking constant-pixel-level patterns in ICDMtp-HG02.* containing 9 gray levels.



6.1 GRAY SCALE

ALIAS: gamma, electro-optical transfer function (EOTF), tone scale

DESCRIPTION: We measure the luminance for nine, seventeen, or more levels of gray to characterize the gray scale, which is the relationship $L(V)$ between the gray-shade luminance L and the gray-level V . Optionally, the color of each gray shade may also be measured. **Units:** cd/m^2 .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Certain patterns are appropriate to different types of displays. See introductory comments in this chapter (6). We recommend nine or 17 evenly spaced levels — for details see the appendix A12 Images and Patterns for Procedures and especially § A12.1.1 Rendering Gray and Color Levels.

PROCEDURE: Display and measure each of $M = 9, 17$, or more gray test patterns from black to white. The test patterns should have center areas that represent evenly spaced gray levels from black to white, $j = 1, 2, \dots, M$.

ANALYSIS: No calculation is required; these are data to be used in later calculations. Plot the luminance data to decide whether the measured display exhibits any strange behavior. The measured data can be used for the determination of gamma.

REPORTING: Report the luminance values at each gray level.

COMMENTS: For certain applications it may be useful to explore more than nine or seventeen levels. It may be necessary to explore all the levels of gray from black to white or any segments in that scale. For example, it may be useful to examine the first 10 levels from black and the last 10 levels to white. This procedure can easily be extended to provide such a detailed coverage of the gray scale.

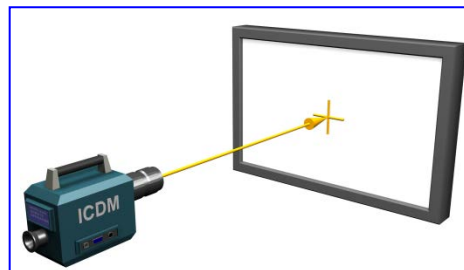


Fig. 1. Center measurement of gray scale.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting Example

Level index, j	Gray Level, V_j	Luminance, L_j (cd/m^2)
9	White(9)	255
8	Level 8	223
7	Level 7	191
6	Level 6	159
5	Level 5	127
4	Level 4	95
3	Level 3	63
2	Level 2	31
1	Black (1)	0

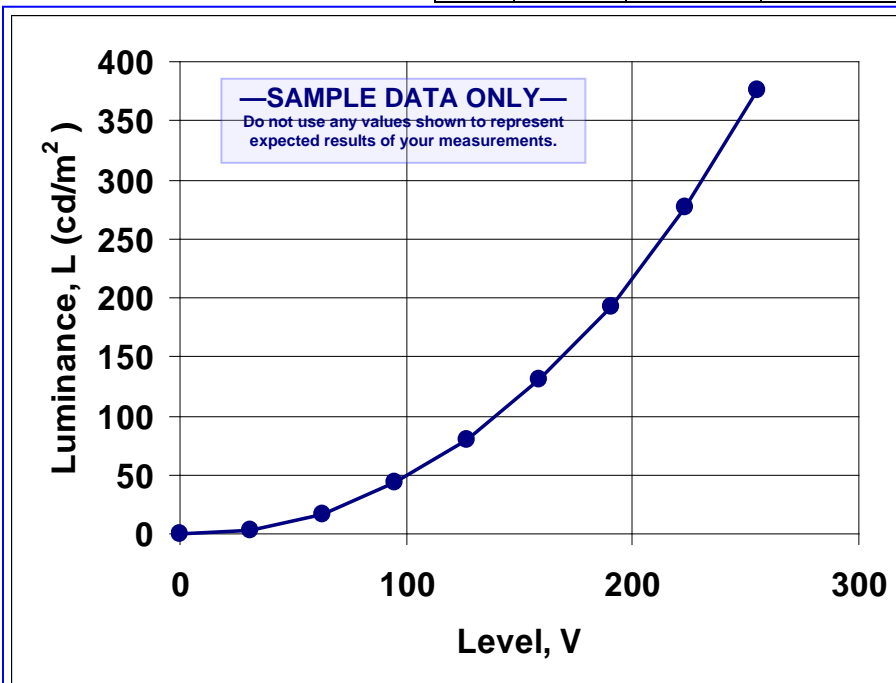


Fig. 2. Plot of gray-scale sample data.



6.2 PRIMARY COLOR SCALES

ALIAS: color gamma, color electro-optical transfer function (EOTF).

DESCRIPTION: Luminance scales (and optionally the color) of the primary colors are measured at nine, 17, or more color levels for each primary color. **Units:** cd/m^2

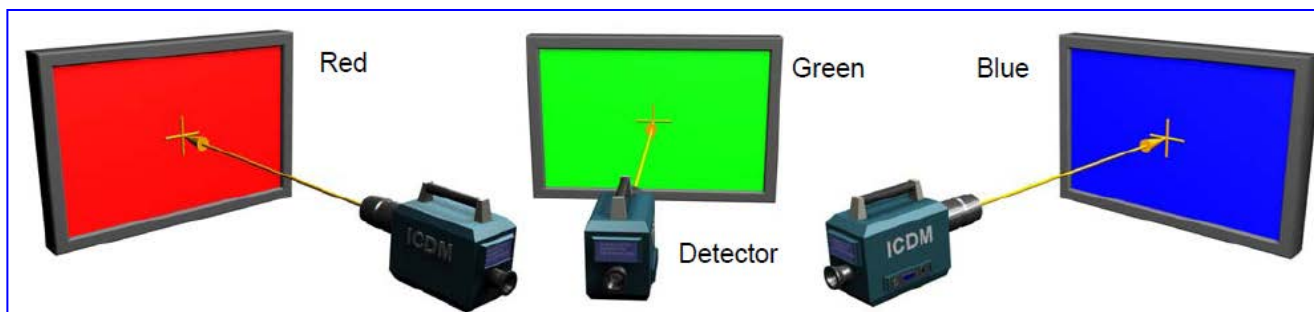


Fig.1. Full-screen patterns of primary colors are shown here, but other patterns may be more suitable depending upon the display technology.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Certain patterns are appropriate to different types of displays. See introductory comments in this chapter (6). We recommend nine or 17 evenly spaced levels — for details see the appendix A12 Images and Patterns for Procedures. Each primary color is measured separately.

PROCEDURE: Display and measure the luminance (optionally the color) of each of nine, seventeen, or more primary-color test patterns from black to the maximum primary color level. The test patterns should provide evenly spaced color levels.

ANALYSIS: No calculation is required. Plot the luminance data to decide whether the measured display exhibits any strange behavior. The measured data can be used for gamma determination of each color primary. See the Fig. 3 below for an example.

REPORTING: Report the luminance values of the color levels to no more than three significant figures for each primary color. See the table below for an example.

COMMENTS: (1) **Nine Levels Minimum:** The minimum number of primary color levels should be nine. For special purposes it may be useful to explore more than nine or seventeen levels. It may be necessary to explore all the levels of primary colors from black to the maximum levels of the primary colors or any segments in that scale. (2) **Non-Primary Colors:** Colors that fall inside the color gamut of the display are mixes of the primaries (secondary colors fall approximately on the gamut lines and are not considered interior colors). Except for white, all the interior colors use intermediate levels of at least one of the primaries. If more than one level of a certain color is required, the model used to mix the levels of the primary colors in order to define that special interior color scale must be determined to the satisfaction of all interested parties. The above specification (at the start of this chapter) for bit levels in software or analog signal levels does not apply to interior colors except for white. The above measurement procedure can easily be extended to accommodate these special requirements. (3) **Levels and Patterns:** The command color levels can follow the measuring method § 6.1 Gray Scale above. Test patterns also can be similarly to the gray-scale measuring method § 6.1 above.

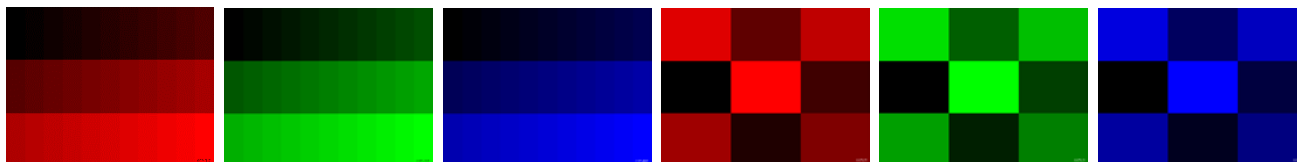


Fig. 2. Constant-picture-level patterns that cycle the various color levels at the center: CCPLR##, CCPLG##, CCPLB##, for 33 levels, and CCPLR#, CCPLG#, CCPLB# for nine levels. These are found in pattern collections ICDMtp-HG01, 02 at <https://doi.org/10.55410/igam8989>.

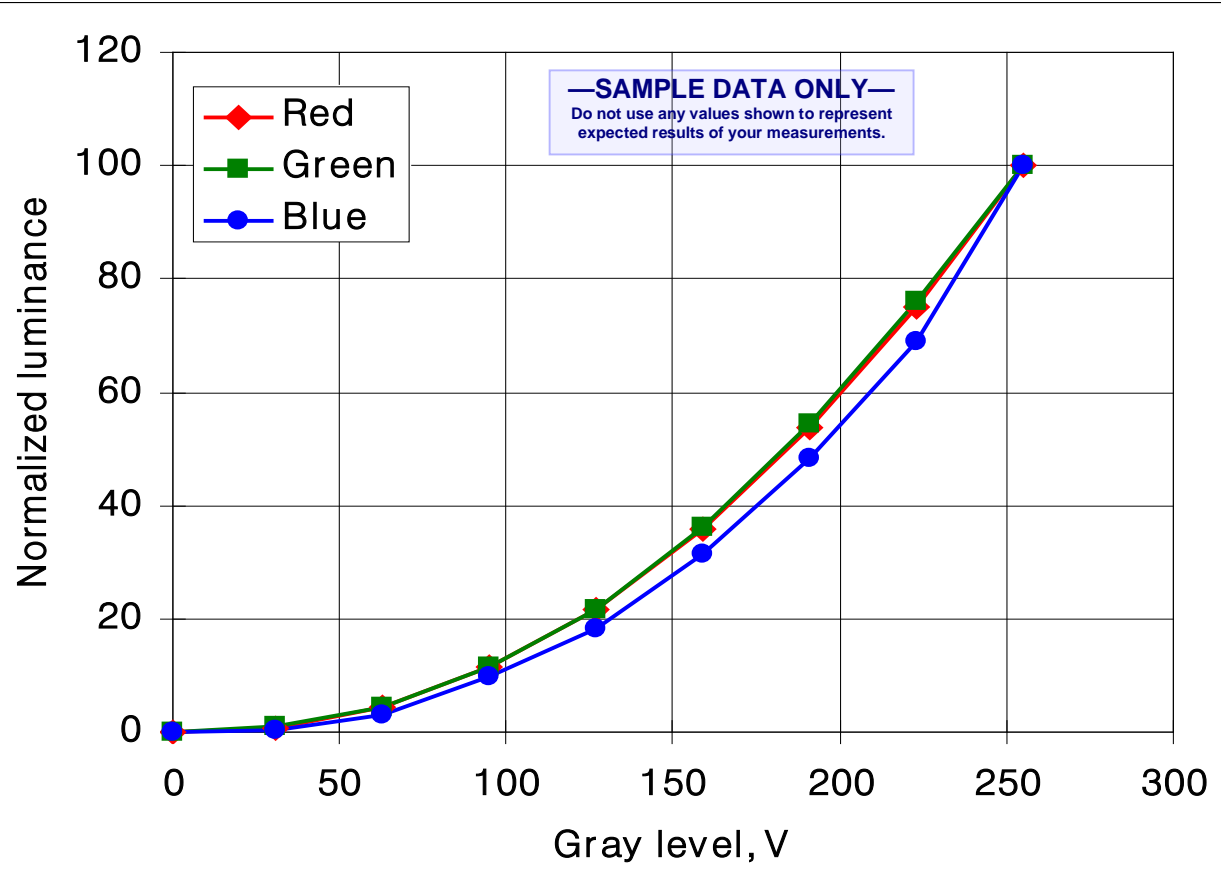


Fig. 3. Comparison of different "gammas" for RGB & S.

—SAMPLE DATA ONLY—							
Do not use any values shown to represent expected results of your measurements.							
Analysis – Color Scales							
Level Number (Index)	Scale V_j	Red Luminance	Green Luminance	Blue Luminance	Normalized Red	Normalized Green	Normalized Blue
Maximum (9)	255	102.2	378	57.2	100	100	100
Level 8	223	76.6	287.6	39.4	75.0	76.1	68.9
Level 7	191	55.0	205.1	27.6	53.8	54.3	48.3
Level 6	159	36.5	136.8	17.9	35.7	36.2	31.3
Level 5	127	22.0	81.4	10.4	21.5	21.5	18.2
Level 4	95	11.74	43.09	5.65	11.49	11.40	9.88
Level 3	63	4.60	16.98	1.80	4.50	4.49	3.15
Level 2	31	0.801	3.371	0.29	0.784	0.892	0.507
Black (1)	0	0.031	0.031	0.031	0.0303	0.0082	0.0542



6.3 LOG-LOG GAMMA DETERMINATION

ALIAS: gamma, electro-optical transfer function (EOTF).

DESCRIPTION: The gamma values for the data taken from § 6.1 Gray Scale and § 6.2 Primary Color Scales are calculated based upon a log-log fit to the data. **Units:** none **Symbol:** γ .

APPLICATION: All displays that exhibit gray levels that can be mathematically characterized by a power-law of the input signal. **NOTE:** If there is an inversion of the gray scale such that some gray shade is darker than the black shade, then this method does not work; that is, if $L_j < L_K$ for any $j > 2$ then do not use this method to calculate gamma, use § 6.5 Model-Fitting Gamma Determination.

SETUP: None, a calculation based upon data already obtained in sections 6.1 Gray Scale and 6.2 Primary Color Scales.

PROCEDURE & ANALYSIS: (We are using “log” to mean \log_{10} , “ln” will be used for natural logs.)

1. Obtain the gray scale and/or color scale data from sections 6.1 Gray Scale and/or § 6.2 Primary Color Scales for the M selected levels.
2. If it hasn't been done already, plot the gray shade luminance values against the gray-level bit values.
3. For each luminance level j above black ($j > 1$) determine the **net luminance** as the luminance increase over black, $\Delta L_j = L_j - L_K$, $j = 2, 3, \dots, M$, where $L_K = L_1$ is black.
4. For each level $j > 1$, calculate $\Delta V_j = V_j - V_1$, $j = 2, 3, \dots, M$, where V_j is the gray level and $V_1 = V_K$ is the gray level for black and is often zero.
5. Calculate $\log(\Delta L_j)$ for each gray shade $j > 1$.
6. Calculate $\log(\Delta V_j)$ for each gray level $j > 1$.
7. Create a log-log plot between the log of the net luminance $\Delta L_j = L_j - L_K$ and the log of the net gray level differences (or signal level differences) $\Delta V_j = V_j - V_1$, $j = 2, 3, \dots, M$, where $V_1 = V_K$.
8. Perform a linear regression of $\log(\Delta L_j)$ vs. $\log(\Delta V_j)$ for $j = 2, 3, \dots, M$, and record the correlation coefficient. The linear regression returns a value for γ and the intercept b of the vertical axis in the log-log plot.

The simple mathematical model $L(V)$ for this analysis is:

$$L(V_j) = a(V_j - V_K)^\gamma + L_K, \quad (1)$$

or terms of logs,

$$\log[L(V_j) - L_K] = \gamma \log(V_j - V_K) + \log(a) \quad (2)$$

This has the linear form $y = mx + b$, where $m = \gamma$ is the slope and $b = \log(a)$ is the intercept of the fitted line with the vertical axis (the ordinate) at location 0 on the horizontal axis (abscissa). Our constant is given by:

$$a = 10^b. \quad (3)$$

Many types of software provide automated fitting to straight-line data.

REPORTING: Report the gray scale data set, the method used, the resulting gamma value, and the parameter a . Report the gamma γ value and a to no more than three significant figures.

COMMENTS: (1) Why Fit to Log-Log?: Some may argue that a nonlinear fit to the luminance data would provide a better model (see § 6.5), while the log-log fitting method is specified in this section. However, the eye is relatively insensitive to small changes in the higher luminance levels, so fitting to the log-log data can give a better fit to the lower luminance levels. Furthermore, many are more comfortable with the ease-of-use of the

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Analysis – Gamma of Gray (or Color) Scale					
Level Number (Index)	Gray Level, V_j	Gray Shade Luminance, L_j (cd/m ²)	Net Luminance $\Delta L_j = L_j - L_K$ (cd/m ²)	$\log(V_j - V_1)$	$\log(\Delta L_j)$
White(9)	255	376.5	376.15	2.4065	2.5754
Level 8	223	276.9	276.55	2.3483	2.4418
Level 7	191	193.2	192.85	2.2810	2.2852
Level 6	159	130.8	130.45	2.2014	2.1154
Level 5	127	79.03	78.68	2.1038	1.8959
Level 4	95	42.95	42.6	1.9777	1.6294
Level 3	63	16.88	16.53	1.7993	1.2182
Level 2	31	3.542	3.19	1.4914	0.5038
Black (1), $V_1 = V_K =$	0	0.352			
Log-Log Gamma, $\gamma =$			2.25		
$a = 10^b$			0.00144		cd/m ²
Correlation Coefficient =			0.9998		



log-log slope extraction. (2) **Goodness of Fit:** If a gamma value is calculated and reported for data that do not fit this simple model well, it should be noted in the comments of a report form. If not all the data are used to calculate a gamma then the data used to calculate the gamma value should be reported. The correlation coefficient r^2 should be larger than 0.98;

otherwise the correlation coefficient should be reported. (3) **Data Taking Order:** Occasionally, the gray scale measurement results including the resulting gamma value can be changed according to the order in which the gray scale is measured (ascending and descending).

(4) **Spreadsheet:** A spreadsheet illustrating this fitting process is included with the printed copy of this document, see the file

Gray-and-Color-Scales.xls.

Full details of the use of such spreadsheets may be found in the help information supplied with the spreadsheets. Here are two brief examples:

Excel®: The LINEST formula must be entered as an array formula. Select a range of two columns and five rows starting with the LINEST [example:

=LINEST(M6:M13,J6:J13,TRUE,TRUE)] formula cell in the upper left corner. Press F2, and then press CTRL+SHIFT+ENTER. You obtain the results shown in the shaded part of Table 1.

OpenOffice®: The LINEST formula is written similarly as above and simply pressing

CTRL+SHIFT+ENTER it creates a 2×5 array of numbers as illustrated in the shaded part of Table 1.

(5) **Better Models:** This log-log metric is included for reasons of legacy (FPDM2 304-2) and its common use in the industry. We recommend that you consider using § 6.5 Model-Fitting Gamma Determination (GOGO Model) as a replacement for this model.

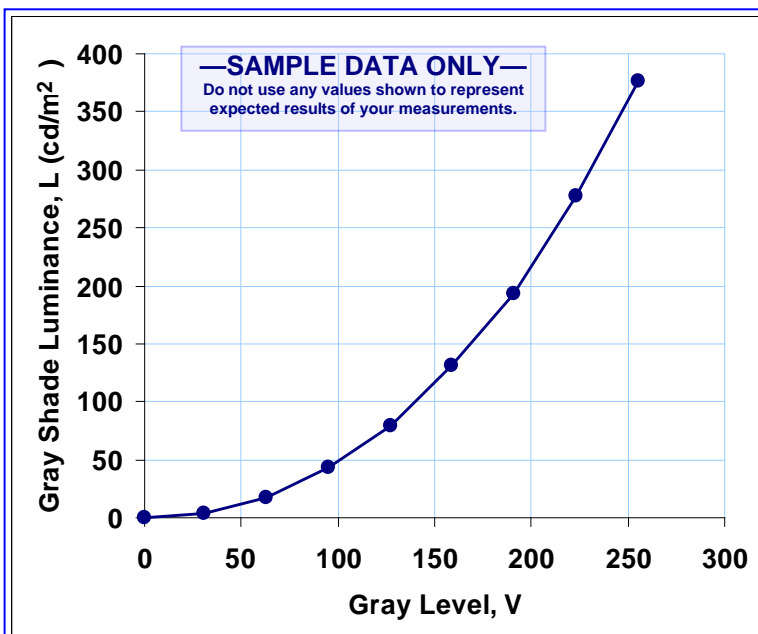


Fig.1. Sample luminance vs. gray level.

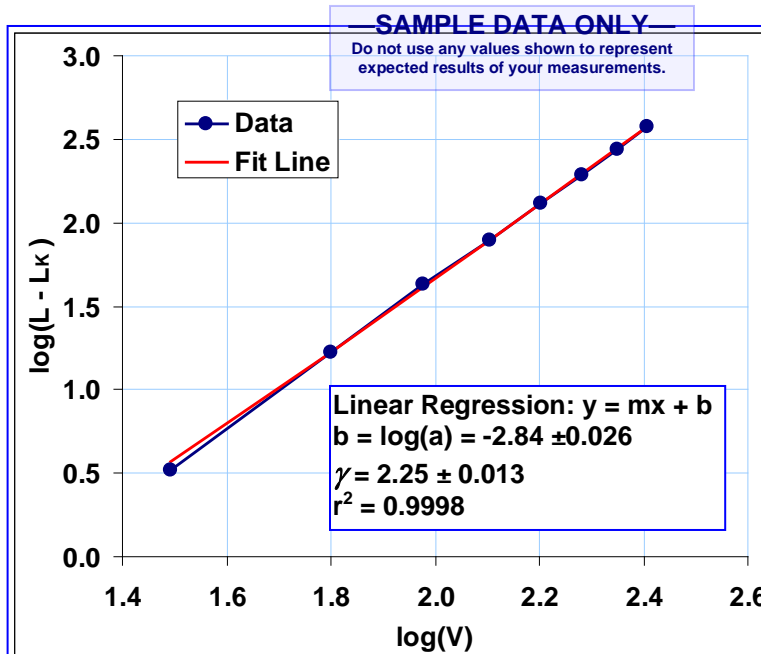


Fig.2. Sample log-log plot of luminance vs. gray level.

Table 1. Fit results for LINEST formula for Excel® and OpenOffice® spreadsheets.			
Slope, Gamma, γ =	2.2513	-2.841	Intercept, $b = \log(a)$
Uncertainty of slope, σ_γ =	0.01276	0.026743	Uncertainty of Intercept, σ_b
Correlation Coefficient r^2	0.9998	0.01044	Standard Deviation L_j Values
F statistic	31140	6	Degree of Freedom (9 L_j Values)
Regression Sum of Squares	3.3955	0.000654	Residual Sum of Squares

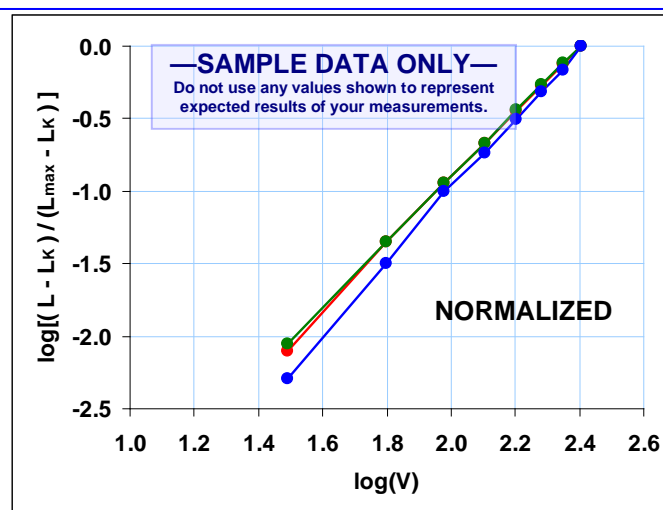
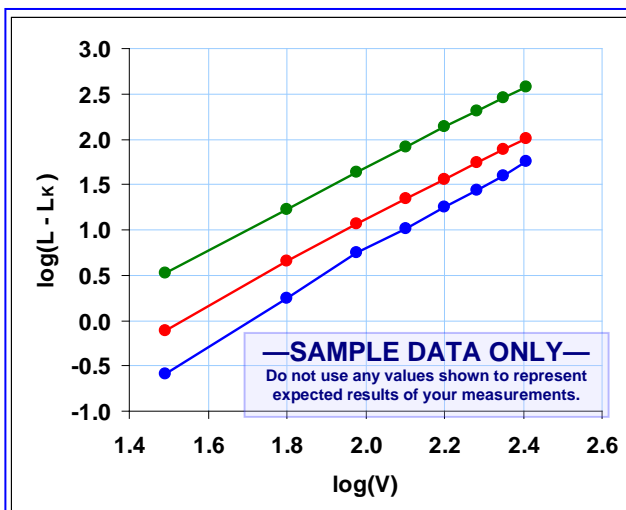
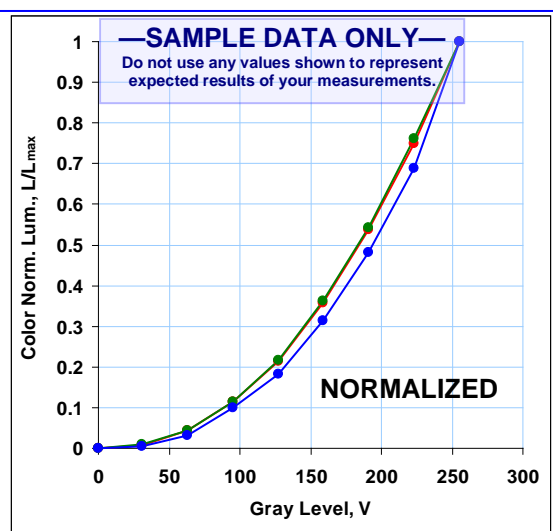
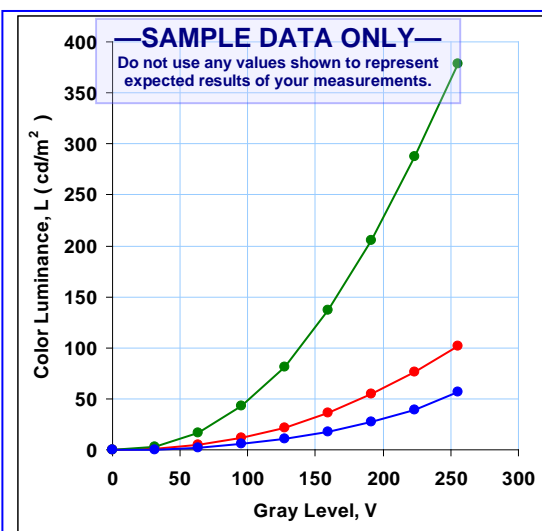


6.4 LOG-LOG COLOR GAMMA DETERMINATION

This is an extension of § 6.3 above as applied to the individual primary colors, RGB. Each primary color may have a gamma value that is slightly different from the combined gray-scale gamma. In comparing them graphically, it is helpful to normalize the data as shown in the graphs below.

Note: These log-log metrics are included for reasons of legacy (FPDM2 304-2) and their common use in the industry. We recommend that you consider using § 6.5 Model-Fitting Gamma Determination (GOGO Model) as a replacement for this model.

Level Number (Index)	Color Level, V	Red Luminance, L_R (cd/m ²)	Green Luminance, L_G (cd/m ²)	Blue Luminance, L_B (cd/m ²)
White(9)	255	102.2	378	57.2
Level 8	223	76.6	287.6	39.4
Level 7	191	55	205.1	27.6
Level 6	159	36.5	136.8	17.9
Level 5	127	22	81.4	10.4
Level 4	95	11.74	43.09	5.65
Level 3	63	4.6	16.98	1.8
Level 2	31	0.801	3.371	0.29
Black (1) V_1 & $L_1 = L_K$	0	0.031	0.031	0.031
Gamma, $\gamma =$		2.30	2.25	2.53
$b = \log(a) =$		-3.52	-2.82	-4.32
$r =$		0.9990	0.9999	0.99839
$a = 10^b =$		3.05E-04	1.51E-03	4.79E-05





6.5 MODEL-FITTING GAMMA DETERMINATION (GOGO MODEL)

ALIAS: gamma, electro-optical transfer function (EOTF)

DESCRIPTION: We perform a nonlinear-least-squares fit of the gray-scale or a color-scale data using a four-parameter fitting function (called a GOGO model, see References below). **Units:** no units **Symbol:** γ .

SETUP & PROCEDURE: No setup or measurement procedure is required. This is a calculation based upon data collected in previous sections.

ANALYSIS: We show a nonlinear-least-squares fit to gray-scale data in Fig. 1 for an example. The fitting function $l(V_i)$ that is used to fit the *normalized* luminances employs normalized levels as inputs:

$$l(V_i) = l_0 + g \left(\frac{V_i}{V_W} + v_0 \right)^\gamma \cong \frac{L_i(V_i)}{L_W}, \quad (1)$$

where l_0 is called the first offset, g is called the gain,

v_0 is called the second offset, and γ is the gamma we

want to determine. We define the difference between the normalized luminance and the model function and the sum of these squared differences:

$$\Delta_i = \frac{L_i(V_i)}{L_W} - l(V_i), \quad S = \sum_i \Delta_i^2 \quad (2)$$

The objective is to find the best parameter values (l_0 , g , v_0 , γ) that minimize the sum of the squares of the differences, S . A variety of programming tools can be used to perform this kind of fit. The following constraints should be imposed upon the fitting process: $l_0 \geq 0$, $g \geq 1$, $v_0 \geq 0$, and γ can be set to anything initially, try $\gamma = 2$, for example.

1. Calculate the normalized luminance L_i/L_W and normalized levels V_i/V_W values for each gray or color level.
2. Calculate the predicted luminance based upon Eq. (1).
3. Determine the differences Δ_i and the sum of the squares of the differences, S .
4. Extract the best fit value of γ from a nonlinear fitting routine.

REPORTING: Report the gray or color scale data set, the method used, and the fitting parameters with the resulting gamma value.

COMMENTS: (1) **Methods:** Two gamma determination methods are suggested in this standard that have almost the same values. Any determination method can be selected by user. If another fitting function other than that expressed in Eq. (1) is used, then it must be explicitly stated in any reporting documentation. (2) **Fitting Tools:** Any statistical tool such as SAS®, Minitab®, Origin®, PSI-Plot®, Excel®, OpenOffice®, and many others may be used to fit the data to the function in Eq. (1). We show examples of using Excel® Solver and OpenOffice® Solver below.

This nonlinear fitting using a four-parameter fit in Eq. (1) can have different manifestations. If we fix $l_0 = 0$ or nearly so, then a three parameter model results called the GOG model (see references 1 and 2). It is essential that whatever fitting model is used, log-log, GOGO, or GOG, the model employed must be reported along with all the fitting parameters in addition to the gamma value. *It is not reasonable to just report a value for gamma without identifying the model used to establish that value.*

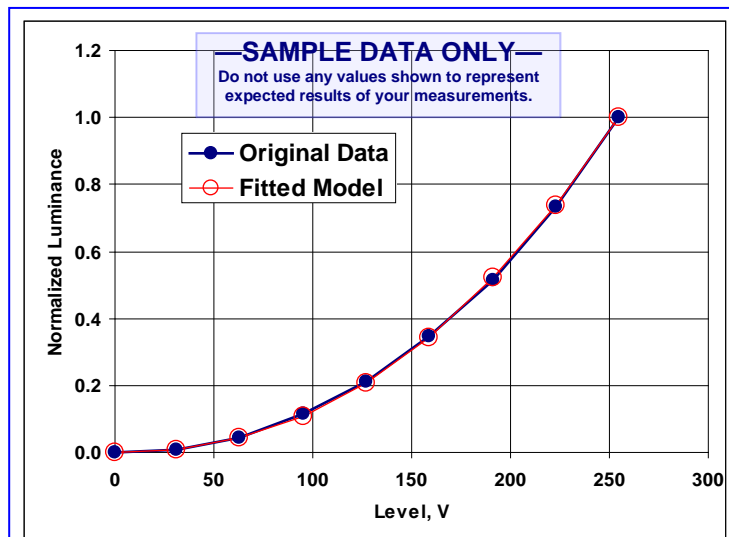


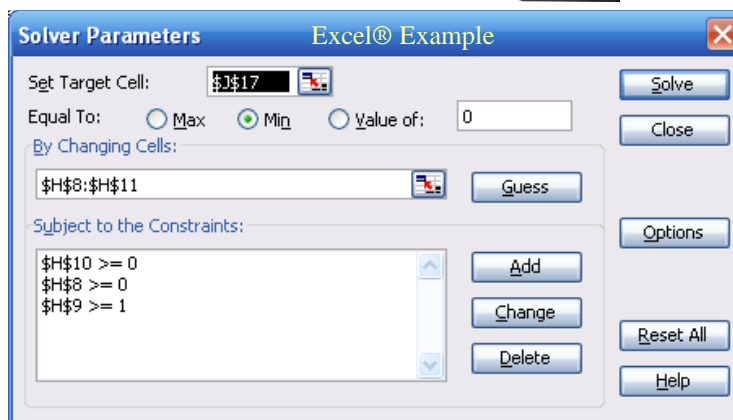
Fig. 1. Least squares fit to data gray-scale data.

Reporting – Sample Data		
Model-Fitting Gamma		
Level #	Gray Level, V	Luminance, L (cd/m ²)
White(9)	255	376.5
Level 8	223	276.9
Level 7	191	193.2
Level 6	159	130.8
Level 5	127	79.03
Level 4	95	42.95
Level 3	63	16.88
Level 2	31	3.542
Black (1)	0	0.352
Model		GOGO
l_0		0.001045
g		1
v_0		0
γ		2.26



(a) **Example for Excel® Using SOLVER:** Run Solver (Tools/Solver): We show an example window below of what the Solver window looks like in one version of Excel®. (If Solver is not available in the Tools menu, then go to Tools, select Add-Ins and select Solver, and Solver will then be added to the Tool menu. In the Solver Parameters window do the following:

- **Set Target Cell:** Cell with SUM(Differences Squared) [yellow cell below]
- **Equal To:** Select Value of: enter 0 (probably already there)
- **By Changing Cells:** select the four parameter values in the model [cyan cells below]
- **Subject to the Constraints:** fill in the constraints on the parameters
- When you hit **Solve** the parameter values will be changed from your initial guessed values to new values that best fit the data. Note that if your selection of initial parameters is not very good, the fitting may not work. It is always best to select parameter values that provide a fitting function that is somewhat close to the data, if possible.
- See the spreadsheet Gray-and-Color-Scales.xls supplied with the printed copy of this document for an example.

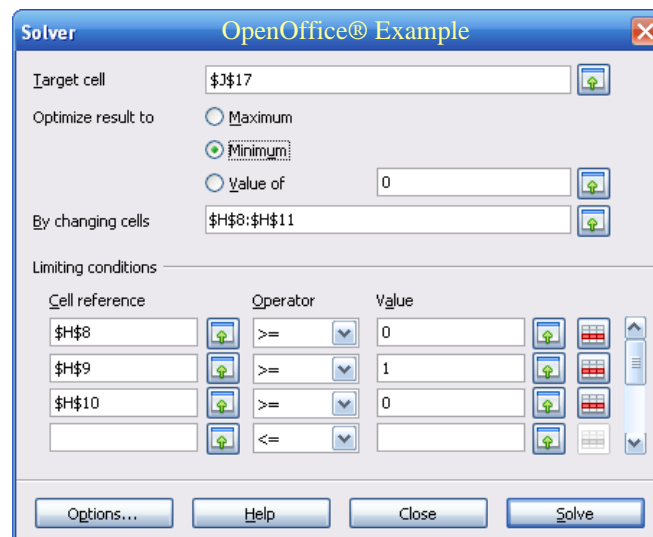


B	C	D	E	F	G	H	I	J
Level Number, Index i	Level, V_i	Luminance, L_m (cd/m ²)	V_i/V_W	L_i/L_W	Fitting Parameters		Model Result $I(V)$ from Parameters	Δ^2
White(9)	255	376.5	1.0000	1.0000	$I_0 =$	0.00104541	1.0010	1.093E-06
Level 8	223	276.9	0.8745	0.7355	Gain, $g =$	1	0.7393	1.472E-05
Level 7	191	193.2	0.7490	0.5131	$v_0 =$	0	0.5210	6.148E-05
Level 6	159	130.8	0.6235	0.3474	$\gamma =$	2.2632	0.3444	9.148E-06
Level 5	127	79.03	0.4980	0.2099	Constraints:		0.2075	5.728E-06
Level 4	95	42.95	0.3725	0.1141	$I_0 \geq 0$		0.1081	3.600E-05
Level 3	63	16.88	0.2471	0.0448	$g \geq 1$		0.0433	2.375E-06
Level 2	31	3.542	0.1216	0.0094	$v_0 \geq 0$		0.0095	1.572E-08
Black (1)	0	0.352	0.0000	0.0009			0.0010	1.221E-08
							sum(Δ^2) =	1.31E-04

(b) **Example for OpenOffice® Using SOLVER:** Run Solver (Tools/Solver) similarly as for Excel®.

REFERENCES: There are a variety of fitting functions that could be used to fit these data: Here we employ a gain-offset-gamma (GOG) model that is suggested by Berns et al in 1993 and modified by Katoh et al. in 1997 to be called the gain-offset-gamma-offset (GOGO) model.

1. R. S. Berns, R. J. Motta, and M. E. Gorzynski, "CRT colorimetry. Part I: Theory and practice", Color Res. Appl. 18, 299-314 (1993).
2. R. S. Berns, R. J. Motta, and M. E. Gorzynski, "CRT colorimetry. Part II: Metrology", Color Res. Appl. 18, 315-325 (1993).
3. N. Katoh and T. Deguchi, "Reconsideration of CRT monitor characteristics", Proc. IS&T/SID Fifth Color Imaging Conference (IS&T, Springfield, VA, 1997) pp. 33-39.
4. EBU Tech. 3273-E, <http://tech.ebu.ch/publications>.





6.6 STANDARD DEVIATION OF GAMMA

DESCRIPTION: The standard deviation of gamma is calculated to evaluate the performance of a display gamma using the deviation of the slope of the log-log fitting of the data. In addition, the correlation coefficient and the deviation of the intercept also can be calculated and compared. The data are obtained from previous measurements in sections 6.1 Gray Scale and 6.2 Primary Color Scales and the analysis in § 6.3 Log-Log Gamma Determination.

The data of § 6.3 Log-Log Gamma Determination are repeated here:

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Gray Scale Data from § 6.36 Log-Log Gamma Determination					
Level Number (Index)	Gray Level, V_j	Gray Shade Luminance, L_j (cd/m ²)	Net Luminance $\Delta L_j = L_j - L_K$ (cd/m ²)	$\log(V_j - V_1)$	$\log(\Delta L_j)$
White(9)	255	376.5	376.15	2.4065	2.5754
Level 8	223	276.9	276.55	2.3483	2.4418
Level 7	191	193.2	192.85	2.2810	2.2852
Level 6	159	130.8	130.45	2.2014	2.1154
Level 5	127	79.03	78.68	2.1038	1.8959
Level 4	95	42.95	42.6	1.9777	1.6294
Level 3	63	16.88	16.53	1.7993	1.2182
Level 2	31	3.542	3.19	1.4914	0.5038
Black (1), $V_1 = V_K =$	0	0.352			
Gamma, $\gamma =$			2.24		
$a = 10^b$			0.00154		cd/m ²
Correlation Coefficient =			0.9999		

ANALYSIS: The analysis is provided by standard software packages. Examples are provided in § 6.36 Log-Log Gamma Determination for two spreadsheet programs. Here are typical results obtained:

Table 1. Fit results for LINEST formula for Excel® and OpenOffice® spreadsheets.			
Slope, Gamma, $\gamma =$	2.2384	-2.8118	Intercept, $b = \log(a)$
Uncertainty of slope, $\sigma_\gamma =$	0.01026	0.02151	Uncertainty of Intercept, σ_b
Correlation Coefficient r^2	0.99987	0.008398	Standard Deviation L_j Values
F statistic	47596	6	Degree of Freedom (9 L_j Values)
Regression Sum of Squares	3.3566	0.0004231	Residual Sum of Squares

REPORTING: Report the gamma, the intercept, and their absolute and relative standard deviations.

COMMENTS: Acceptable Ranges: The range of acceptable standard deviation of gamma, the standard deviation of the intercept and the correlation coefficient can be established between manufacturers and users.

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting – Sample Data	
Gamma, γ	2.24
Standard deviation of Gamma, σ_γ	0.0103
in %	0.46 %
Intercept, b	-2.81
Standard deviation of intercept, σ_b	0.0215
in %	0.76 %

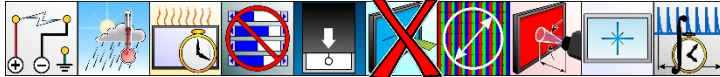


6.7 DIRECTIONAL GAMMAS

DESCRIPTION: We measure the gray scale at center screen and at four angles about the screen normal—up, down, left, right—as needed. The angles used depend upon the needs of the users and would be agreed upon by all interested parties. The ideal display device has a characteristic that the gamma values are constant in any viewing directions. This method measures how the gamma values change from the usually viewing direction. **Units:** none **Symbol:** γ .

NOTE: We have an entire chapter, Chapter 9, devoted to viewing-angle properties. Please refer to it for additional viewing-angle metrics.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



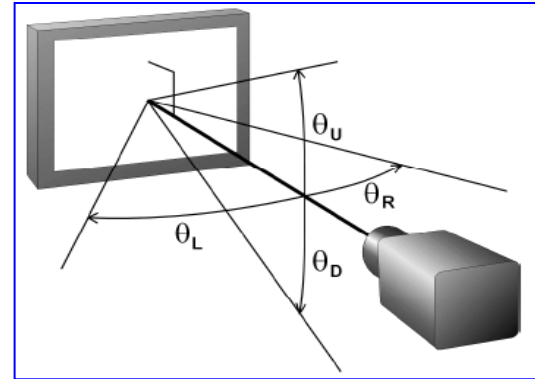
OTHER SETUP CONDITIONS: Certain patterns are appropriate to different types of displays. See introductory comments in this chapter (6). We recommend nine or 17 evenly spaced levels — for details see the appendix A13 Images and Patterns for Procedures.

PROCEDURE: Display and measure the luminance (optionally the color) of each of nine, seventeen, or more primary-color test patterns from black to white or the maximum primary color level. The test patterns should provide evenly spaced color levels.

ANALYSIS: Analyze the gray-scale luminances at each angle using the method in § 6.3 Log-Log Gamma Determination in order to obtain a gamma value for each viewing angle. These gamma values may be used in calculations in the subsections following this section.

REPORTING: Report the data and the gamma values for normal direction and the four other angles.

COMMENTS: (1) **Viewing Direction:** Some displays are intended to be viewed from a direction not along the normal, such as may be found in cockpits and automobiles. This method can be adapted accordingly using viewing-angle coordinates. (2) **Color Gammas:** This method may also be directly adapted to the gammas of the color primaries. See § 6.10. (3) **Extension:** We show this for four angles about the normal. This method can be extended to many angles over a wide viewing region; for example, all the angles from 0° to 85° in 5° steps. (4) **Graphing:** It is useful to present a graph of the data to see how the gray scale changes with viewing angle. (5) **Corners:** For some technologies combined viewing angles up and to the side may produce more pronounced effects on gamma than just up, down, right, and left.



—SAMPLE DATA ONLY—

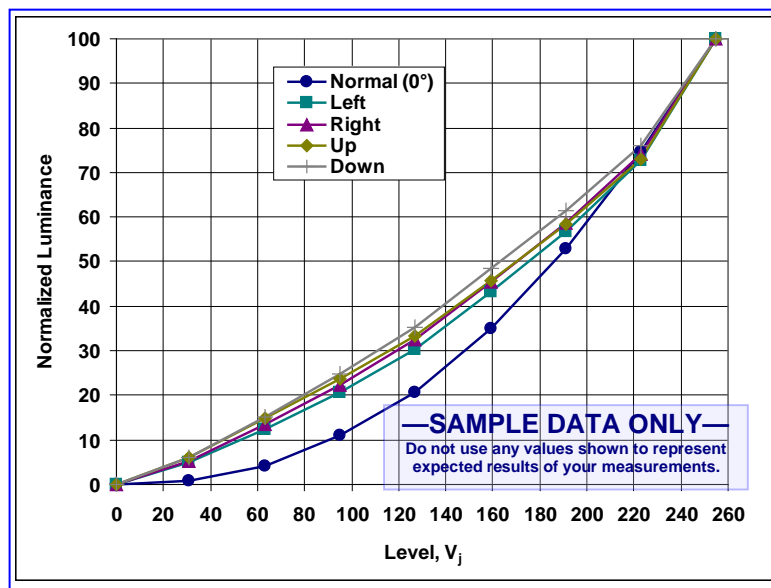
Do not use any values shown to represent expected results of your measurements.

Reporting — Sample Data

Gray-Scale Luminance and Gamma Values at Various Angles

Level Designation	Gray Level, V_j	Gray scale from different angles (θ) *				
		Normal, L_j 0°	Left, θ_L -20°	Right, θ_R 20°	Up, θ_U 20°	Down, θ_D -20°
White(9)	255	555.7	181.2	180.3	160.8	164.7
Level 8	223	415.5	131.9	133.8	117.6	125.3
Level 7	191	293.6	102.7	105.8	93.9	101.3
Level 6	159	194.9	78.3	82.2	73.6	80
Level 5	127	115.1	54.7	58.7	53.8	58.2
Level 4	95	60.83	37.24	40.23	38.12	40.83
Level 3	63	23.53	22.47	24.14	24	25.06
Level 2	31	4.488	8.75	9.535	9.918	10.03
Black (1)	0	0.031	0.058	0.056	0.073	0.067
Gammas:		2.29	1.41	1.37	1.28	1.30
$\gamma, \gamma_L, \gamma_R, \gamma_U$		$= \gamma$	$= \gamma_L$	$= \gamma_R$	$= \gamma_U$	$= \gamma_D$

* Note that the angles shown here are examples; they are not necessarily the angles you should use.





6.8 DIRECTIONAL GAMMA-DISTORTION RATIO

DESCRIPTION: We calculate the ratio of the largest deviation of the gamma from the normal-direction gamma over the range of gammas obtained in § 6.7 Directional Gammas. **Units:** % **Symbol:** g_{DR}

PROCEDURE: Obtain the five (or more) directional gamma values from § 6.7 Directional Gammas for the gray scale.

ANALYSIS: The directional gamma distortion is calculated as follows:

$$g_i = \frac{|\gamma - \gamma_i|}{\gamma} \times 100\%,$$

where γ is the reference gamma value (usually taken from the normal direction at screen center) and γ_i are the gammas measured from the different directional angles, $\gamma_i = \gamma_L, \gamma_R, \gamma_U$, and γ_D . The directional gamma-distortion ratio is the maximum of this set of values:

$$g_{DR} = \max(g_i),$$

where $\max(g_i) \equiv \max(g_L, g_R, g_U, g_D)$. The average is

$$g_{DRave} = \frac{1}{n} \sum_{i=1}^n g_i,$$

where n is the number of gamma values measured other than the normal; in the case described here, $n = 4$. The minimum deviation, $\min(g_i)$, may also be of interest.

REPORTING: The largest gamma distortion ratio might be reported. Depending on the needs, in some cases, the average gamma distortion ratio, or the entire table of gamma distortion ratio also can be reported as shown below.

COMMENTS: Note that other viewing angle metrics may be found in Chapter 9 that involve lightness and chroma metrics.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Reporting — Directional Gamma Distortion Analysis – Sample Data					
Measuring Location	Center, γ	Left, γ_L	Right, γ_R	Up, γ_U	Down, γ_D
Gammas	2.29	1.41	1.37	1.28	1.30
g_i		38.6%	40.3%	44.0%	43.2%
$g_{DR} = \max(g_i)$		44.0 %			
$\min(g_i)$		38.6 %			
Average: g_{DRave}		41.5 %			



6.9 DIRECTIONAL RMS GRAY-SCALE DISTORTION

DESCRIPTION: We calculate the RMS (root-mean-square) of the deviation of the normalized luminances at various angles compared to the normal direction. **Units:** None. **Symbol:** gRMS

PROCEDURE: Obtain the luminance data and gammas from § 6.7 Directional Gammas.

ANALYSIS: The directional gamma distortion RMS is calculated from the gray scale data set of each direction as shown in the table below.

—SAMPLE DATA ONLY—											
Do not use any values shown to represent expected results of your measurements.											
Gray-Scale Data							Normalized Gray-Scale Data				
Level Designation (Index)	Level, V_j	Reference	Gray scales at different angles				Ref.	Normalized, from different angles			
		Gray L_j	Left	Right	Up	Down	Normal	Left	Right	Up	Down
		Normal (0°)	20°	20°	20°	20°	0°	20°	20°	20°	20°
White(9)	255	555.7	181.2	180.3	160.8	164.7	1	1	1	1	1
Level 8	223	415.5	131.9	133.8	117.6	125.3	0.74771	0.72792	0.74210	0.73134	0.76078
Level 7	191	293.6	102.7	105.8	93.9	101.3	0.52834	0.56678	0.58680	0.58396	0.61506
Level 6	159	194.9	78.3	82.2	73.6	80	0.35073	0.43212	0.45591	0.45771	0.48573
Level 5	127	115.1	54.7	58.7	53.8	58.2	0.20713	0.30188	0.32557	0.33458	0.35337
Level 4	95	60.83	37.24	40.23	38.12	40.83	0.10947	0.20552	0.22313	0.23706	0.24791
Level 3	63	23.53	22.47	24.14	24	25.06	0.042343	0.124007	0.133888	0.149254	0.15215
Level 2	31	4.488	8.75	9.535	9.918	10.03	0.008076	0.048289	0.052884	0.061679	0.06090
Black (1)	0	0.031	0.058	0.056	0.073	0.067	5.579E-05	0.0003201	0.0003106	0.000454	0.00041

For each direction $D = \text{Left, Right, Up, Down}$, and for each measured luminance value L_{Dj} between white and black ($j = 1, 2, 3, \dots, M-1$), we define a quantity Δx_{Dj} ($\Delta x_{Dj} = \Delta x_{\text{Left}j}, \Delta x_{\text{Right}j}, \Delta x_{\text{Up}j}, \Delta x_{\text{Down}j}$) that compares the normalized reference values L_j (assumed to be taken from the normal direction) with the normalized luminances for each direction:

$$\Delta x_{Dj} = 100 \left[\frac{L_{Dj}}{L_{DW}} - \frac{L_j}{L_W} \right], \quad j = 1, 2, 3, \dots, M-1.$$

We define an arithmetic mean of the squares (RMS) of these differences to obtain another measure of how the gamma curves differ:

$$g_{\text{RMSD}} = \sqrt{\frac{1}{M-2} \sum_{j=1}^{M-1} \Delta x_{Dj}^2}.$$

The minimum and luminance values are not included for this calculation, because the normalized-maximum luminances each have same value of 1.

REPORTING: Depending on the needs. The largest gamma distortion RMS might be reported. In some cases, the average gamma distortion RMS, or the entire table of gamma distortion RMS also can be reported as shown below table.

COMMENTS: For special purposes, directional gamma distortion may be useful to explore more than four angles against the reference angle. It may be necessary to explore all the angles from 0 degree to 85 degree by 5 degree steps. Absolute luminance difference values also can be used for calculation of directional gamma distortion RMS instead of using normalized luminance difference.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Directional gamma distortion Analysis – Sample Data					
Measuring Location	Normal	Left	Right	Up	Down
Gamma	2.29	1.41	1.36	1.28	1.30
gRMS for Left, Right, Up, Down:	7.07	8.61	9.38	10.78	
Max gRMSD	10.78				
Min gRMSD	7.06				
Mean gRMSD	8.96				



6.10 COLOR GAMMA-DISTORTION RATIO

DESCRIPTION: We calculate a metric to describe how the primary (RGB) color gammas differ from the gray-scale gamma. The ideal display device has a characteristic that the gamma values are constant in RGB primary color channel. In order to measure a display device that how the gamma values are changed from a different primary color channel, the “RGB gamma distortion ratio” is measured and calculated. **Units:** % **Symbol:** g_{DRcol} .

SETUP& PROCEDURE: None. Use the data collected in § 6.2 Primary Color Scales and § 6.1 Gray Scale with their gamma determinations in § 6.3 Log-Log Gamma Determination and § 0 Log-Log Color Gamma Determination where all the measurements are made on the same displa. Note that different data may be illustrated here than illustrated in previous sections.

ANALYSIS: The RGB gamma distortion ratio is calculated from the color scale data set as shown below tables.

1. Calculate 4 gamma values for gray scale and color scales data set using gamma determination method
2. Calculate the gamma distortion ratio according to below equation

$$g_{DRcol} = 100\% \frac{|\gamma - \gamma_Q|}{\gamma},$$

where g_{DRcol} is the gamma distortion ratio for the primary colors, γ is a reference gamma value obtained from the gray scale in § 6.3, and γ_Q is the color gamma values, $Q = R, G, B$. Here, we again employ the notation $\max(x_i) \equiv \max(x_1, x_2, \dots)$; that is, we are obtaining the maximum of a series of numbers.

REPORTING: Depending on the needs. The largest gamma distortion ratio might be reported. In some cases, the average gamma distortion ratio, or the entire table of gamma distortion ratio also can be reported as shown below table.

COMMENTS: Max g_{DRcol} is normally recommended, however, some statistical values for g_{DRcol} such as average and minimum values also can be used. Graphical information also can be shown using each normalized gray scale values to see how the gamma distortion is occurred from different angles.

Level Number	Color Level, V_i	Gray Shade Luminance, L (cd/m ²)	Red-Shade Luminance, L (cd/m ²)	Green-Shade Luminance, L (cd/m ²)	Blue-Shade Luminance, L (cd/m ²)
White(9)	255	555.7	102.2	378	57.2
Level 8	223	415.5	76.6	287.6	39.4
Level 7	191	293.6	55	205.1	27.6
Level 6	159	194.9	36.5	136.8	17.9
Level 5	127	115.1	22	81.4	10.4
Level 4	95	60.83	11.74	43.09	5.65
Level 3	63	23.53	4.6	16.98	1.8
Level 2	31	4.488	0.801	3.371	0.29
Black (1) V_1 & $L_1 = L_K$	0	0.031	0.031	0.031	0.031

—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Color scale distortion Analysis – Sample Data				
	Gray	Red	Green	Blue
Gamma	2.29	2.31	2.25	2.53
g_{DRcol} (%)		1.56	4.00	24.1
Max g_{DRcol} (%)		24.1		
Min g_{DRcol} (%)		1.56		
Mean g_{DRcol} (%)		4.00		

6.11 COLOR-SCALE RMS DISTORTION

DESCRIPTION: We calculate the root-sum-of-squares (RMS) of the difference between the gray and color scales.

The ideal display device has a characteristic that the gamma values are the same for all RGB primary colors and the gray scale as well. RGB gamma distortion ratio is useful to measure how the gamma is different for each primary color scale. The gamma distortion from RGB channel, however, is not fully explained using that slope comparison of EOTF. Some gamma distortion is shown differently in different color level, so the other type of metric is required. The “Directional gamma distortion RMS,” therefore, is calculated to explain those distortions. **Units:** % **Symbol:** g_{RMScol} .

SETUP& PROCEDURE: None. Use the data collected in § 6.2 Primary Color Scales and § 6.1 Gray Scale with their gamma determinations in § 6.3 Log-Log Gamma Determination and § 0 Log-Log Color Gamma Determination where all the measurements are made on the same display. Note that different data may be illustrated here than illustrated in previous sections.

ANALYSIS: The RGB gamma distortion RMS is calculated from the color scale data set as shown the table below.

- (1) Calculate the normalized luminance difference Δx_{Qi} between reference gray and the colors, and M is the number of gray levels that are used for the gray and color-scale measurements. The maximum luminance value is not included for this calculation, because the normalized maximum luminance is always the same.



$$\Delta x_{Qj} = 100 \left[\frac{L_{Qj}}{L_{QW}} - \frac{L_j}{L_W} \right]$$

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Color RMS Gamma Distortion Analysis – Sample Data

Level Number	Color Level, V_i	Gray-Shade Lum., L_i (cd/m ²)	Red-Shade Lum., L_{Ri} (cd/m ²)	Green-Shade Lum., L_{Gi} (cd/m ²)	Blue-Shade Lum., L_{Bi} (cd/m ²)	Norm'd Gray	Norm'd Red	Norm'd Green	Norm'd Bue	Δx_{Ri}	Δx_{Gi}	Δx_{Bi}
White(9)	255	555.7	102.2	378	57.2	1	1	1	1			
Level 8	223	415.5	76.6	287.6	39.4	0.74771	0.74951	0.76085	0.68881	0.181	1.314	-5.889
Level 7	191	293.6	55	205.1	27.6	0.52834	0.53816	0.54259	0.48252	0.982	1.425	-4.583
Level 6	159	194.9	36.5	136.8	17.9	0.35073	0.35714	0.36190	0.31294	0.641	1.118	-3.779
Level 5	127	115.1	22	81.4	10.4	0.20713	0.21526	0.21534	0.18182	0.814	0.822	-2.531
Level 4	95	60.83	11.74	43.09	5.65	0.10947	0.11487	0.11399	0.09878	0.541	0.453	-1.069
Level 3	63	23.53	4.6	16.98	1.8	0.04234	0.04501	0.044921	0.031469	0.267	0.258	-1.087
Level 2	31	4.488	0.801	3.371	0.29	0.008076	0.007838	0.008918	0.005070	-0.024	0.084	-0.301
Black (1)	0	0.031	0.031	0.031	0.031	0.0000558	0.0003033	8.2011E-05	0.0005420	0.025	0.003	0.049

(2) Calculate the gamma distortion RMS according to the equation

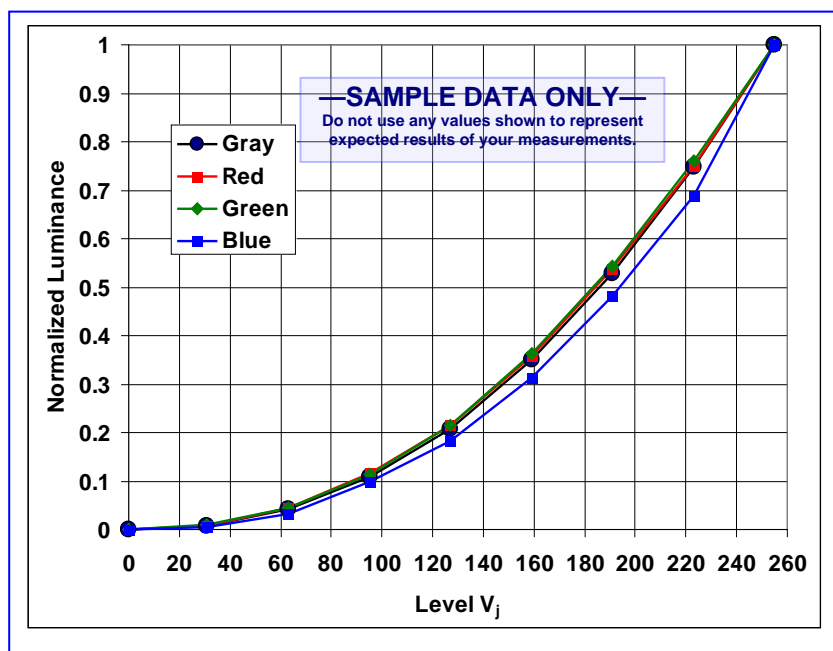
$$g_{\text{RMScol}} = \sqrt{\frac{1}{M-2} \sum_{i=1}^{M-2} \Delta x_i^2}$$

where g_{RMScol} is the RMS value for gamma distortion for the primary colors referenced to the gray shades.

REPORTING: Depending on the needs. The largest gamma distortion RMS might be reported. In some cases, the average gamma distortion RMS, or the entire table of gamma distortion RMS also can be reported as shown below table.

COMMENTS: Absolute luminance difference values also can be used for calculation of RGB gamma distortion RMS instead of using normalized luminance difference.

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Reporting — Color RMS Gamma Distortion			
	Red	Green	Blue
g_{RMScol}	0.59	0.92	3.35
Max g_{RMScol}	3.35		
Min g_{RMScol}	0.59		
Mean g_{RMScol}	1.62		

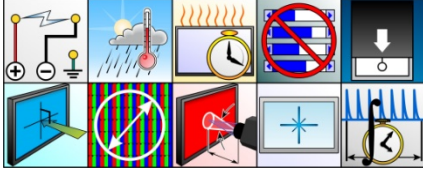




6.12 POSITIONAL GAMMA-DISTORTION RATIO

DESCRIPTION: We measure the gray scale at the center and in several positions on the screen and compare the gamma values at each location with the gamma value at the center of the screen to determine any positional distortion of the gray scale. **Units:** % **Symbol:** g_{DRpos} .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange the luminance meter to measure the gray scales at five (or nine) locations as shown in Figure 2. Alternatively, the gray scales at each location can be measured through a vantage point (a point in space usually along the normal of the center of the screen).

PROCEDURE: Measure the gray scales in five (or nine) locations as shown in Figure 2.

ANALYSIS: The positional gamma distortion ratio is calculated from the gray scale data set of each position as shown below table.

1. Calculate 5 gamma values for 5 gray scales from different positions using a gamma determination method.
2. Calculate the gamma distortion ratio according to below equation

$$g_{DRposi} = 100\% \frac{|\gamma - \gamma_i|}{\gamma}$$

where g_{DRposi} is gamma distortion ratio based upon a reference gamma value γ (normally, the gamma value of center screen), and γ_i are the gamma values for the other positions.

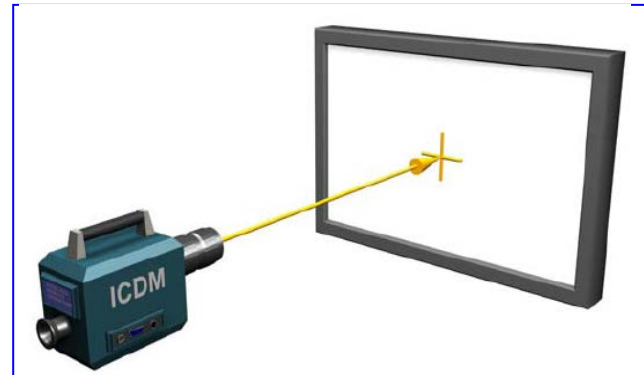
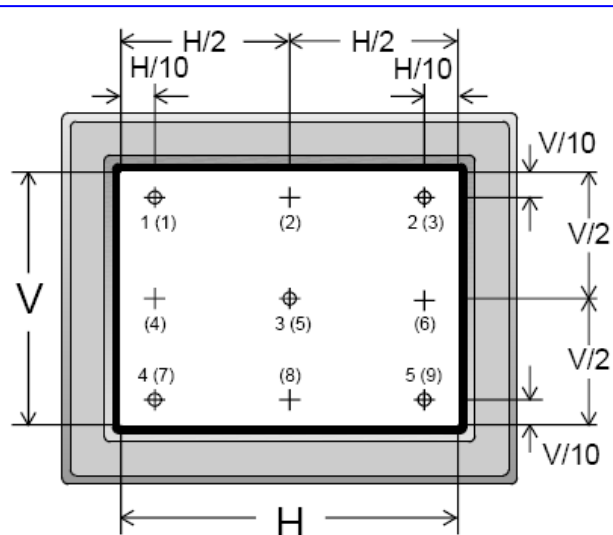


Fig. 1. Center measurement of gray scale.



⊕ Denote 5-point locations. + Denote 9-point locations.
1, 2, 3, 4, 5 (1), (2), (3), ..., (9)

Fig. 2. Measuring locations for gamma uniformity distortion

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis — Gray scale luminances and their gamma values

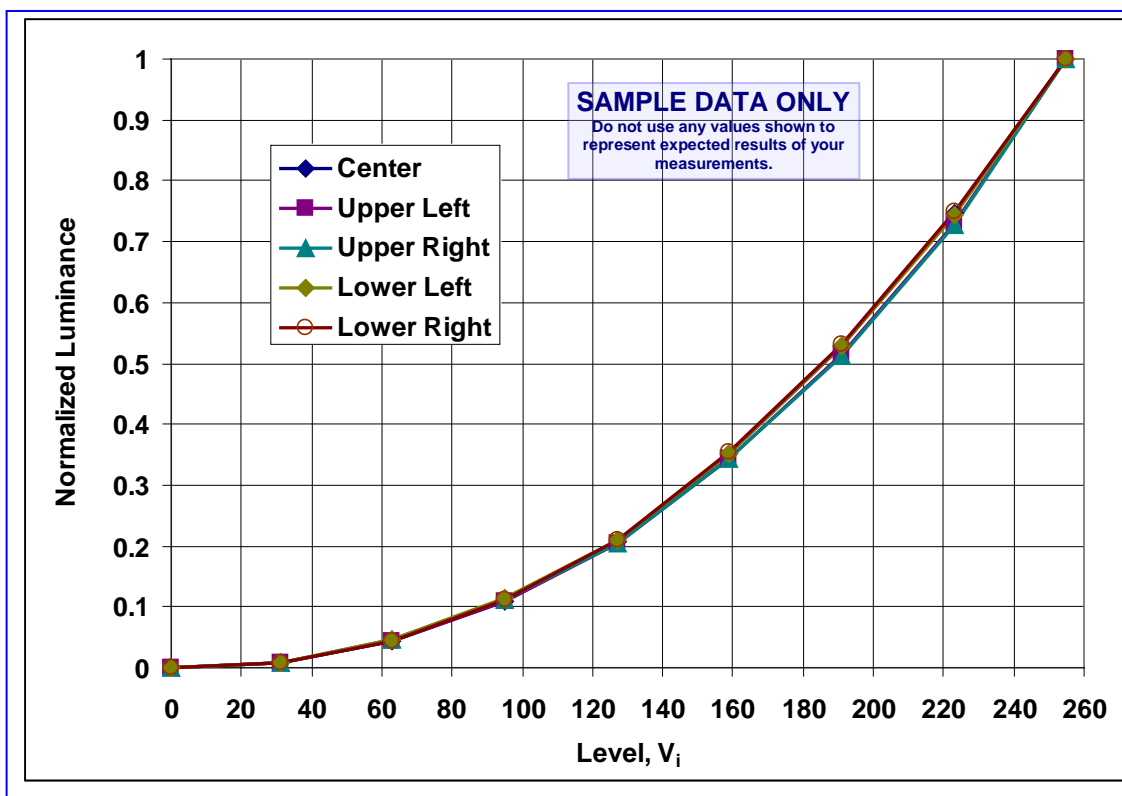
Level Number	Level, V_i	Measuring Locations				
		L_3 (Center)	L_1 (UL)	L_2 (UR)	L_4 (LL)	L_5 (LR)
White(9)	255	555.7	493	474.2	498.6	520.8
Level 8	223	415.5	359.9	344.7	371.1	389.9
Level 7	191	293.6	253.4	242.5	262.9	276.4
Level 6	159	194.9	168.9	162.5	175.9	184.4
Level 5	127	115.1	100.2	97	104.8	109
Level 4	95	60.83	53.95	52.85	56.44	58.1
Level 3	63	23.53	21.53	21.54	22.64	22.65
Level 2	31	4.488	4.309	4.438	4.598	4.351
Black (1)	0	0.031	0.025	0.029	0.028	0.037
	Gamma:	2.29	2.24	2.21	2.22	2.27



REPORTING: Depending on the needs. The largest gamma distortion ratio might be reported. In some cases, the average gamma distortion ratio, or the entire table of gamma distortion ratio also can be reported as shown below table.

COMMENTS: We show a simple luminance meter making discrete measurements in Fig. 1, however there are a number of instruments available that use array detectors and can make these measurements from a vantage point rather than all measurements being made from the normal direction.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Reporting — Positional gamma distortion ratio					
Measuring Location	L_3	L_1	L_2	L_4	L_5
Gamma	2.29	2.24	2.21	2.22	2.27
$gDR_{posi}(\%)$		2.012	3.55	2.87	0.717
Max $gDR_{pos}(\%)$			3.55		
Min $gDR_{pos}(\%)$			0.717		
Mean $gDR_{pos}(\%)$			2.29		





6.13 POSITIONAL GRAY-SCALE RMS DISTORTION

DESCRIPTION: We calculate the root-sum-of-squares (RMS) of the differences between the normalized ($\times 100$) luminance values at the center compared to four perimeter luminance values around the display using data from the previous measurement method. **Units:** % **Symbol:** GD_R .

SETUP & PROCEDURE: Use the data collected from the previous measurement method 6.12 Positional Gamma Distortion Ratio.

ANALYSIS: Let Δx_{Pj} be the normalized ($\times 100$) luminance difference between reference (center) and the perimeter luminances at positions P for measured gray levels $j = 1, 2, \dots, n$ ($n = 9$ in the case shown here) the maximum Δx_{Pn} is not included (they are all the same levels of 100). Calculate the quantities Δx_{Pj} for all perimeter locations P :

$$\Delta x_{Pj} = 100 \left[\frac{L_{Pj}}{L_{PW}} - \frac{L_j}{L_W} \right]. \quad (1)$$

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis — Gray scale luminances and their gamma values

Level Number	Level, V_i	Luminances at Measuring Locations					Normalized (to 100) Luminances				
		L_3 (Center)	L_1 (UL)	L_2 (UR)	L_4 (LL)	L_5 (LR)	$100L_3/L_{3W}$ (Center)	$100L_1/L_{1W}$ (UL)	$100L_2/L_{2W}$ (UR)	$100L_4/L_{4W}$ (LL)	$100L_5/L_{5W}$ (LR)
White(9)	255	555.7	493	474.2	498.6	520.8	100	100	100	100	100
Level 8	223	415.5	359.9	344.7	371.1	389.9	74.77	73	72.69	74.43	74.87
Level 7	191	293.6	253.4	242.5	262.9	276.4	52.73	51.4	51.14	52.73	53.07
Level 6	159	194.9	168.9	162.5	175.9	184.4	35.07	34.26	34.27	35.28	35.41
Level 5	127	115.1	100.2	97	104.8	109	20.71	20.32	20.46	21.02	20.93
Level 4	95	60.83	53.95	52.85	56.44	58.1	10.95	10.94	11.15	11.32	11.16
Level 3	63	23.53	21.53	21.54	22.64	22.65	4.234	4.367	4.542	4.541	4.349
Level 2	31	4.488	4.309	4.438	4.598	4.351	0.808	0.874	0.936	0.922	0.835
Black (1)	0	0.031	0.025	0.029	0.028	0.037	0.006	0.005	0.006	0.006	0.007

Then calculate:

$$g_{RMSposP} = \sqrt{\frac{1}{M-2} \sum_{i=1}^{n-1} \Delta x_{Pi}^2}, \quad (2)$$

where $g_{RMSposP}$ is the RMS value for gray-scale distortion for position P and $n = 9$ is the number of gray level that are used for the gray scale measurement (in this case nine). The maximum luminance values were not included for this calculation because the normalized maximum luminances are always the same values.

REPORTING: Depending on the needs. The largest gamma distortion RMS might be reported. In some cases, the average gamma distortion ratio, or the entire table of gamma distortion RMS also can be reported as shown in the table below. Report any value to no more than three significant figures.

COMMENTS: None.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Gamma uniformity distortion Analysis – Sample Data

Reference Location:	L3	L1	L2	L4	L5
$g_{RMSposP}$	0.927	1.07	0.270	0.201	
Max g_{RMSpos}	1.07				
Min g_{RMSpos}	0.201				
Mean g_{RMSpos}	0.618				

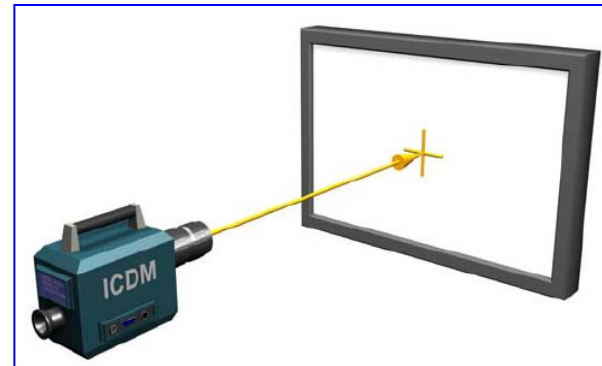
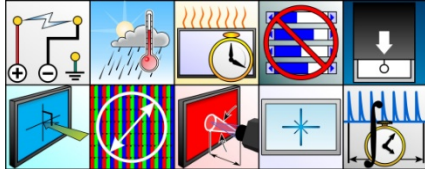


6.14 SLOPE MONOTONICITY OF GRAY SCALE

DESCRIPTION: The slope monotonicity of the gray scale is investigated to determine if there are places where the gray shade does not properly increase with gray level. This metric answers the question: Does the slope of the gray scale continue to increase with gray level. That is, the gray-scale (gamma curve) and its derivative for each gray level luminance should be increasing in a monotonic manner; thus the second derivative must be positive.

Units: None, **Symbol:** None.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE:

Measure the luminance L_i at the center of the screen for each of nine or 17 full-screen gray levels V_i or use data collected in § 6.1 Gray Scale.

ANALYSIS:

Calculate the normalized luminance for each gray level:

$$\bar{L}_i = L_i / L_W, \quad i = 1, 2, \dots, 9$$

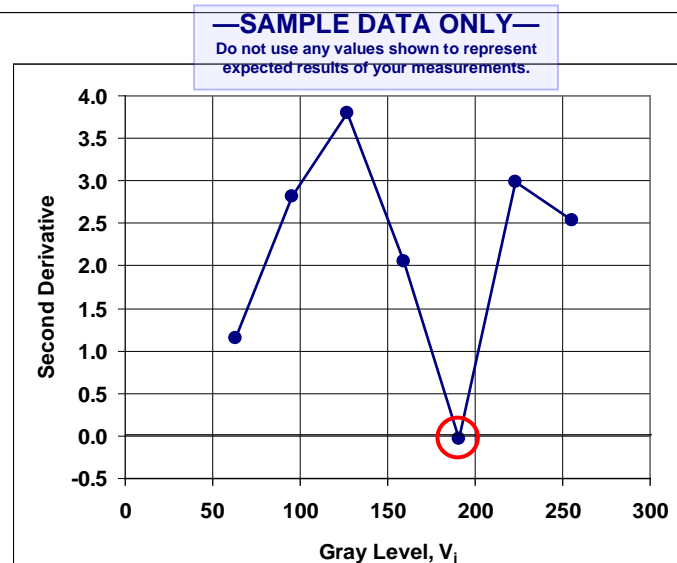
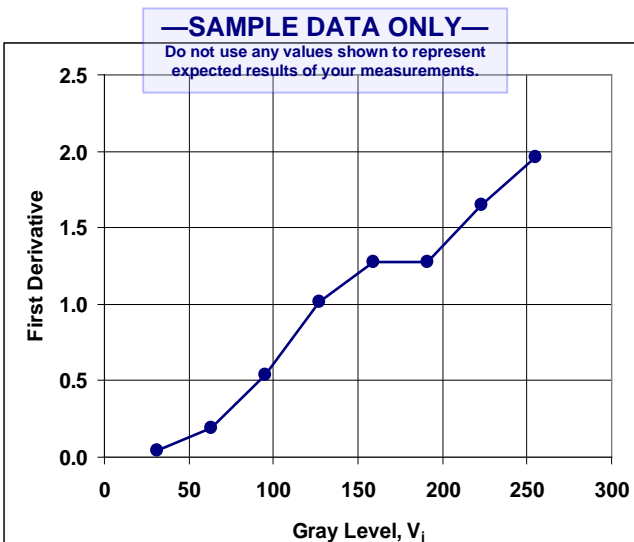
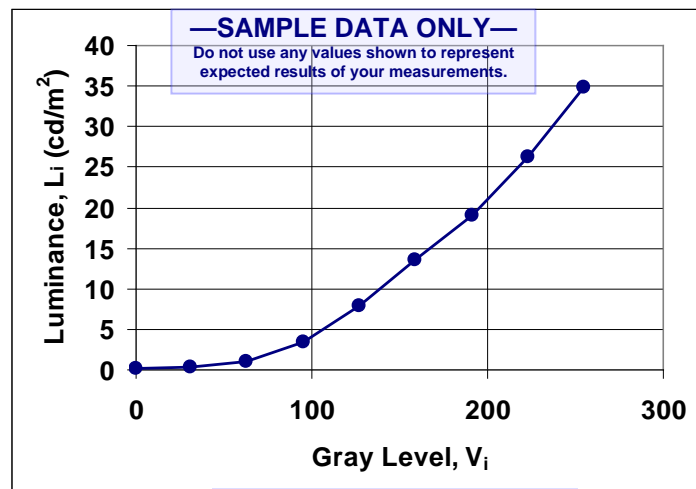
Calculate the normalized gray level:

$$\bar{V}_i = V_i / V_W, \quad i = 1, 2, \dots, 9$$

Calculate the first approximate derivative.

$$\frac{\Delta L_i}{\Delta V_i} = \frac{\bar{L}_i - \bar{L}_{i-1}}{\bar{V}_i - \bar{V}_{i-1}}, \quad i = 2, \dots, 9$$

Calculate the second approximate derivative.





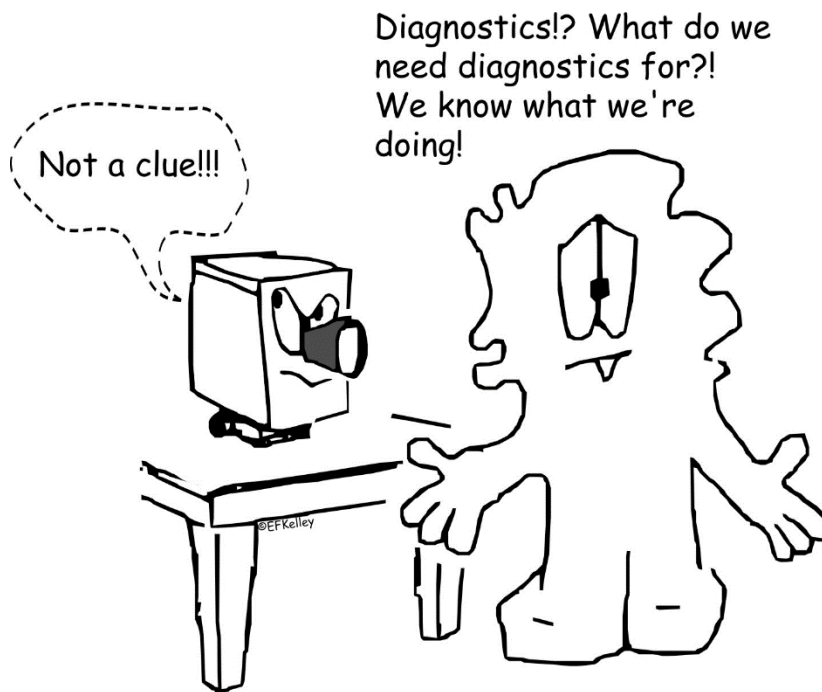
$$\frac{\Delta^2 L_i}{\Delta V_i^2} = \frac{\frac{\Delta L_i}{\Delta V_i} - \frac{\Delta L_{i-1}}{\Delta V_{i-1}}}{\Delta V_i}, \quad i = 3, \dots, 9$$

REPORTING: Report the slope monotonicity of the gray-scale as a table as shown below where any negative value of the second derivative is highlighted.

—SAMPLE DATA ONLY—						
Do not use any values shown to represent expected results of your measurements.						
Gray-Scale Monotonicity Analysis & Reporting						
Level	Gray Level, V_i	L_i	\bar{L}_i	Normalized Levels, \bar{V}_i	1 st Derivative, $\Delta L_i / \Delta V_i$	2 nd Derivative, $\Delta^2 L_i / \Delta V_i^2$
White(9)	255	34.90	1.000	1.000	1.9636	2.5291
Level 8	223	26.30	0.754	0.875	1.6463	2.9840
Level 7	191	19.09	0.547	0.749	1.2718	−0.0364
Level 6	159	13.52	0.387	0.624	1.2764	2.0560
Level 5	127	7.93	0.227	0.498	1.0184	3.8028
Level 4	95	3.47	0.099	0.373	0.5411	2.8275
Level 3	63	1.10	0.032	0.247	0.1863	1.1335
Level 2	31	0.28	0.008	0.122	0.0441	
Black (1)	0	0.1	0.003	0		

COMMENTS: The minimum number of gray level should be larger than eight. For certain applications it may be useful to explore more than nine or seventeen levels, even all the levels of gray or any segments in that scale. For example, it may be useful to examine the first 10 levels from black and the last 10 levels to white. This procedure can easily be extended to provide a detailed coverage of the gray scale. It is recommended that the slope monotonicity of gamma curve value should be larger than zero. Note that noise or uncertainties in the detector may artificially introduce negative second derivatives when the gray shades are close or at either end of the gray scale, white or black.

REFERENCE: EBU Tech. 3273-E, <http://tech.ebu.ch/publications>, 2009.

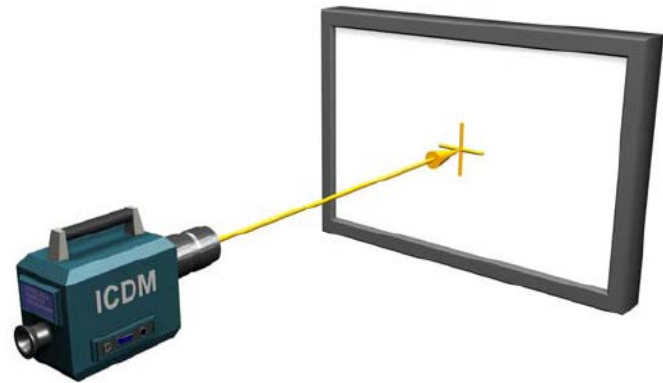
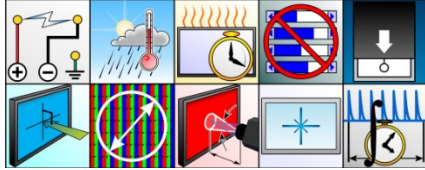




6.15 GRAY-SCALE COLOR CHANGES

DESCRIPTION: We measure the color change $\Delta u'v'$ in nine (or seventeen) gray shades from white to black. Optionally the correlated color temperature (CCT) may also be measured. **Units:** K for CCT and no units for color, **Symbol:** None.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE: Measure the luminance L_i and color

(X_i, Y_i) of the full-screen gray shades at each selected gray level V_i at the center of the screen (optionally include the CCT).

ANALYSIS: Calculate the color difference of each gray shade from the color of white using $\Delta u'v'$. (See § B1.2 Colorimetry in the Tutorial Appendix for formulas for color calculations.)

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis – Sample data

Level Designation	Level, V_i	L_i	x	y	u'	v'	$\Delta u'v'$	CCT
White (9)	255	555.7	0.3264	0.3467	0.0000	0.0000	0.0000	5759
Level 8	223	415.5	0.325	0.3446	-0.1979	-1.4604	0.0013	5825
Level 7	191	293.6	0.3239	0.3432	-0.4027	-2.1500	0.0022	5878
Level 6	159	194.9	0.3233	0.3418	-0.2448	-2.5020	0.0029	5909
Level 5	127	115.1	0.3224	0.342	-0.6663	-2.0225	0.0031	5951
Level 4	95	60.83	0.3221	0.3407	-0.3569	-1.8801	0.0037	5968
Level 3	63	23.53	0.3193	0.3378	-0.4863	-1.7675	0.0058	6113
Level 2	31	4.488	0.3106	0.3236	-0.2109	-1.3652	0.0146	6666
Black (1)	0	0.031	0.2674	0.2689	-0.0083	-0.0356	0.0558	13210
Maximum color change and maximum CCT							0.0558	13210
Average color change and average CCT							0.0112	6809

REPORTING: Depending on the needs, the largest color difference value is recommended to be reported, the average color difference, or the entire table of color difference also can be reported.

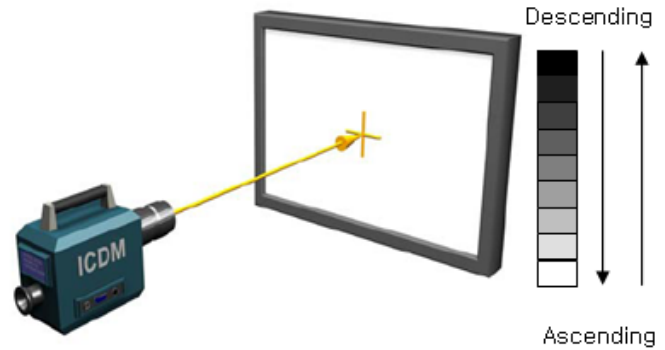
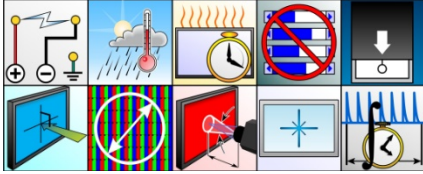
COMMENTS: Generally, color changes when the gray level approaches black are observed in a number of display devices. This is usually not a big problem especially for the black color. For some application this color change can affect the usefulness of the display application. Other ranges of levels may be measured as well as the entire gray scale.



6.16 ORDER DEPENDENCY OF GRAY SCALE

DESCRIPTION: We measure the gray scale at center screen of full-screen gray shades in order of ascending levels and then descending levels and compare the gamma values for each process.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The display must be fully warmed up and stable with less than a 1 % drift per hour while exhibiting a full-white screen. Prepare to show $M = 9$ or more gray shades on the full screen, $i = 1, 2, \dots M$.

PROCEDURE: Measure the luminance L_{di} at the center of the screen for each gray level $i = 1, 2, \dots M$ using the descending order (from white to black); then measure the luminance L_{ai} at the center of the screen for each gray level V_i using the ascending order (from black to white), where $i = 1, 2, \dots M$.

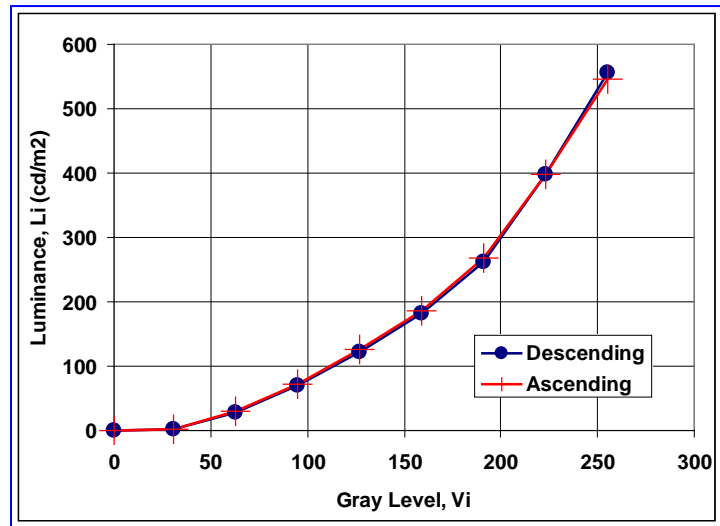
ANALYSIS:

1. Plot the luminance data to compare whether the two data sets exhibit any strange behavior.
2. Calculate each gamma values for ascending data, γ_a , and descending data, γ_d , using § 6.3 Log-Log Gamma Determination. Note the standard deviations of the gamma values, σ_a and σ_d , and intercept, σ_b , from the determinations.
3. Calculate the gamma distortion ratio

$$g_{DRda} = 100\% \frac{|\gamma_a - \gamma_d|}{\gamma_d}$$

4. Calculate the gray-scale RMS distortion values

$$g_{RMSda} = \sqrt{\frac{1}{M-2} \sum_{i=1}^{M-1} \Delta x_{dai}^2}, \text{ where } \Delta x_{dai} = 100 \left[\frac{L_{ai}}{L_{aW}} - \frac{L_{di}}{L_{dW}} \right] \text{ for } i = 1, 2, \dots M-1.$$



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis — Sample Data

Level Designation	V_i	$\downarrow L_{di}$ (cd/m ²)	$\uparrow L_{ai}$ (cd/m ²)	$\log(V_i - V_K)$	$\log(L_{di} - L_{dK})$	$\log(L_{ai} - L_{aK})$	L_{ai}/L_{aK}	L_{di}/L_{dK}	Δx_{dai}	$(\Delta x_{dai})^2$
White (9)	255	555.3	545.1	2.4065	2.7445	2.7364	1	1		
Level 8	223	397.7	398.6	2.3483	2.5995	2.6004	0.7312	0.7162	1.5053	2.2658
Level 7	191	262.4	268.7	2.2810	2.4188	2.4291	0.4929	0.4725	2.0400	4.1615
Level 6	159	182.3	186.9	2.2014	2.2606	2.2714	0.3429	0.3283	1.4582	2.1263
Level 5	127	121.3	126.1	2.1038	2.0836	2.1004	0.2313	0.2184	1.2893	1.6624
Level 4	95	69.29	72.66	1.9777	1.8402	1.8608	0.1333	0.1248	0.8517	0.7254
Level 3	63	28	29.11	1.7993	1.4459	1.4627	0.0534	0.0504	0.2980	0.0888
Level 2	31	2.16	2.44	1.4914	0.3181	0.3711	0.00448	0.00389	0.0586	0.003439
Black (1)	0	0.08	0.09				1.651×10^{-4}	1.441×10^{-4}	0.002104	4.4×10^{-6}



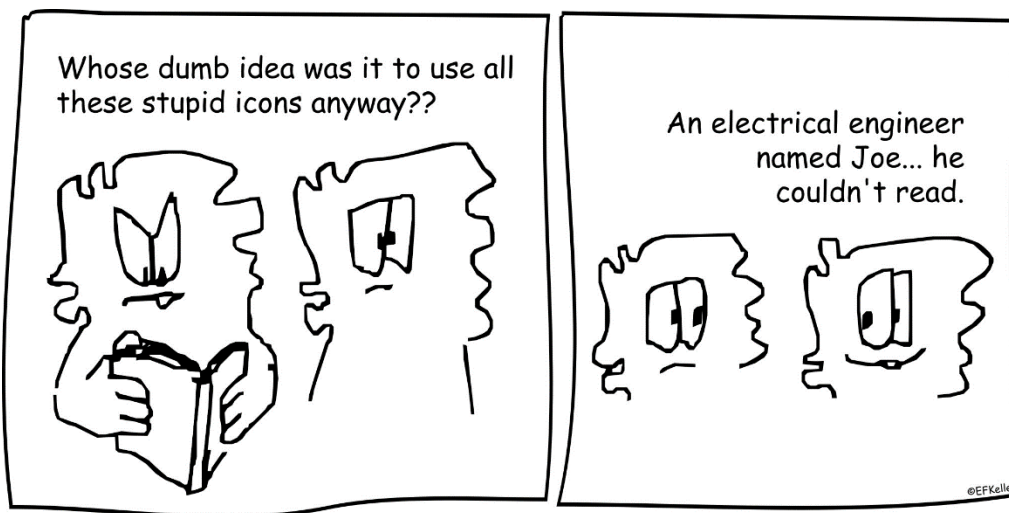
REPORTING: Report the luminance values at each gray level both from ascending and descending gray scale data. Then, gamma values, standard deviation values of slope, standard deviation values of intercept of each data set, and the gamma distortion metric values are reported.

—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Reporting - Sample Data				
	Descending gray-scale data		Ascending gray-scale data	
Gamma values	$\gamma_d =$	2.511	$\gamma_a =$	2.457
Standard deviation of gamma	0.149		0.143	
Standard Deviation of Intercept	0.312		0.300	
Gamma Distortion Ratio	$gDR_{da} =$		2.15 %	
Gray-Scale RMS Distortion	$gRMS_{da} =$		1.26	

COMMENTS: Gray scale test results can differ depending upon the measuring order (ascending and descending) especially in a display technology that dynamically adjust gray levels based on image content. So both ascending and descending gray scale measuring may be required for some specific application.

SCALES

SCALES

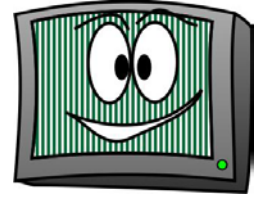




7. SPATIAL MEASUREMENTS

Measuring the ability of the display to properly render detail often amounts to a measurement of high contrasts of small areas—a most difficult measurement to make. If you are not intimately familiar with some of the techniques for accounting for glare, do see the Metrology Appendix and § A2 Stray-Light Management & Veiling Glare, in particular, see § A2.1.6 Correcting for Glare with a Replica Mask and § A2.2 Accounting for Glare in Small-Area Measurements. Here we describe methods to make several measurements of detail luminance, color, and contrast.

Often an array detector (camera, array LMD, etc.) is used to record the detail of the displayed image, even down to the subpixel level. There are a number of concerns in using such array detectors that are outlined in the appendix: A9 Array-Detector Measurements. Keep in mind that in order to capture the detail at a pixel and subpixel level it is often helpful to have from 10 to 30 camera pixels or more per display pixel and/or subpixel—in general, the more camera pixels used per display subpixel the better.



PIXELS AND SUBPIXEL RENDERING FOR RESOLUTION MEASUREMENTS

The first version of this document has been written with great care, expertise and enthusiasm for computer monitors with a distinct fixed relation between subpixels and pixels of a display where each pixel is composed of three subpixels (red, green, and blue). For this class of visual displays, a pixel is defined as the smallest unit that can display the full range of display luminance and chromaticity.

There is another class of displays where there is no fixed relation between the subpixels and the pixels, e.g., some displays with PenTile® subpixel architectures and some RGBW displays. Also, in monitors with color CRTs there is no fixed relation between the individual phosphor dots and the smallest light emitting elements which are determined by the scanning electron beam (its dimensions and its temporal intensity modulation).

It has been shown that the principles laid down in the IDMS can be successfully applied to measurement of the resolution of displays with flexible pixel arrangements. One way to cope with these matters is to give up thinking in terms of pixels, and to start thinking in terms of subpixels instead. This is often referred to as subpixel rendering. The determination of line widths should also be done in terms of subpixels. As soon as the width of the moving window—a single line width—used for averaging of luminance profiles is *not* taken from ill-defined subpixel-to-pixel relationships, the procedure for determination of visual display resolution becomes straightforward and transparent.

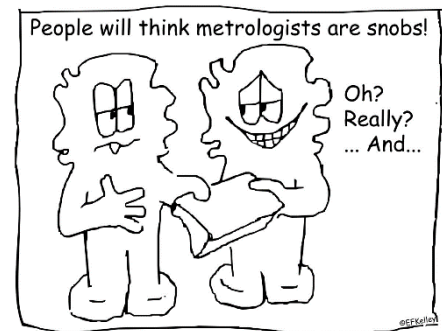
The procedure described in Section 7.2 in conjunction with Section 7.8 provides an approach to the measurement of the visual resolution of display screens. The procedure of Section 7.2 makes sure that this approach can also be applied to advanced subpixel architectures (e.g., to PenTile® layouts, RGBW, RGBY, etc. arrangements) and any type of display technology.

SIGNAL PIXELS AND PATTERNS:

In this chapter, when we speak of applying a pattern or rendering a pattern on a display, we are usually thinking of the signal pixels supplied in the signal and not any rendering on the display. For example, the manufacturer may advertise a maximum pixel array size or capability (advertised resolution) of, for example, 3840×2160 for a display, which may be its native resolution. The signal applied to such a display should exhibit 3840×2160 signal pixels in any pattern. How the display renders that signal will depend upon its display pixel and subpixel structure and electronics. Thus, if we want a single vertical line at center screen in a suitable pattern, the mostly white pattern would be 3840×2160 signal pixels in size and have a black line from top to bottom at the horizontal location 1920 or 1921. By thinking in terms of signal pixels, we can divorce what the display is told to do from what the display does.

NATIVE RESOLUTION & ADVERTISED RESOLUTION

A display will often have a maximum advertised resolution referring to the number of signal pixels it is able to exhibit. This is what we will refer to as the display's native resolution. It may also have other resolutions. For example, a



Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



display may be advertised as having a native resolution of 3840×2160 . It may also have a resolution slightly higher at 4096×2160 that is not advertised as its native resolution, and it may be capable of displaying both resolutions because of subpixel rendering. A grille pattern of 4096×2160 may be displayed differently than a grille pattern of 3840×2160 on such a display. Evaluating how well the display exhibits the grille pattern may depend upon which resolution is selected, and it may be necessary to measure both resolutions. We would certainly test such a display at the advertised native resolution of 3840×2160 . Note that, for a display to list a certain resolution, it must show the black-white 1×1 grilles with achromatic white lines, that is, there must be no color shift visible along the white lines.

LUMINANCE PROFILES AND ARRAY DETECTORS (CAMERAS)

In this chapter, we often speak of a luminance profile across a region of the display. This will often be obtained with an array detector such as a camera. It can be a photopic camera that directly yields the luminance profile, it can be a tristimulus imager that also directly provides a luminance profile as well as color information, or it can be an RGB camera. However, with the RGB camera a transformation must be used to establish the relationship between the RGB output values and the tristimulus values XYZ , at least the luminance Y . There are several ways to establish the correct transformation from camera RGB values to tristimulus values. It is important to note that such an RGB camera must be used in its linear or raw mode where the RGB values are proportional to light being viewed (with any nontrivial background subtracted) and not subjected to a tone curve. Be sure to select an exposure so that the most linear part of the camera image is in use avoiding the low end and the high end as best you can. An exposure that is a multiple of the frame rate interval is wise. See Appendix A16 Color Transformations: RGB to XYZ for more details.

GRILLES AND MOVING-WINDOW AVERAGING

When measuring grilles, we perform a moving-window average on the luminance profile. This can be interpreted as a method to implement what the eye sees at its optimal resolution of 1 min of arc while sitting at an optimal distance from the screen so that a 1×1 grille is resolved by the eye. However, the moving-window averaging can also be interpreted as a method to simply merge the subpixels into visible pixels, and that simulates how we don't see the subpixel structure even when we might be closer than the optimal distance to the display as when many of us use computer monitors.



7.1 LINE LUMINANCE & CONTRAST

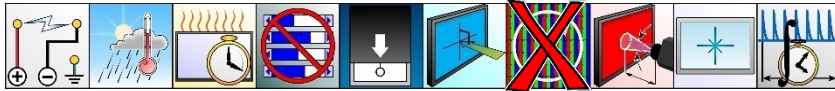
DESCRIPTION: Measure the luminance of a single-pixel vertical (optionally horizontal) black line and the luminance of its white background (positive configuration) attempting to correct for some of the veiling glare in the LMD. Calculate the contrast for the moving-window average of the luminance profile based upon the observed line width. **Units:** cd/m^2 if absolute luminance is needed, none for contrast (a ratio). **Symbol:** C_L .

The display of a black character on a white screen can be one of the most important functions of a display used in a workplace environment. Unfortunately, measuring the luminance or contrast of a black character is difficult and usually very inaccurate. Rather than measuring a character, we recommend a single line in order to provide a more reproducible measurement. See Comments below for more discussion. One contrast metric employed is the ratio of the luminance of the white area L_W to the luminance of the black line L_K

$$C_L = L_W / L_K$$

without glare corruption from, for example, the lens system of the LMD or reflections between the LMD and the display. Other metrics that quantify the visibility of the line may also be employed provided they are documented and all interested parties agree to their use. The Michelson contrast is often of interest as well.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

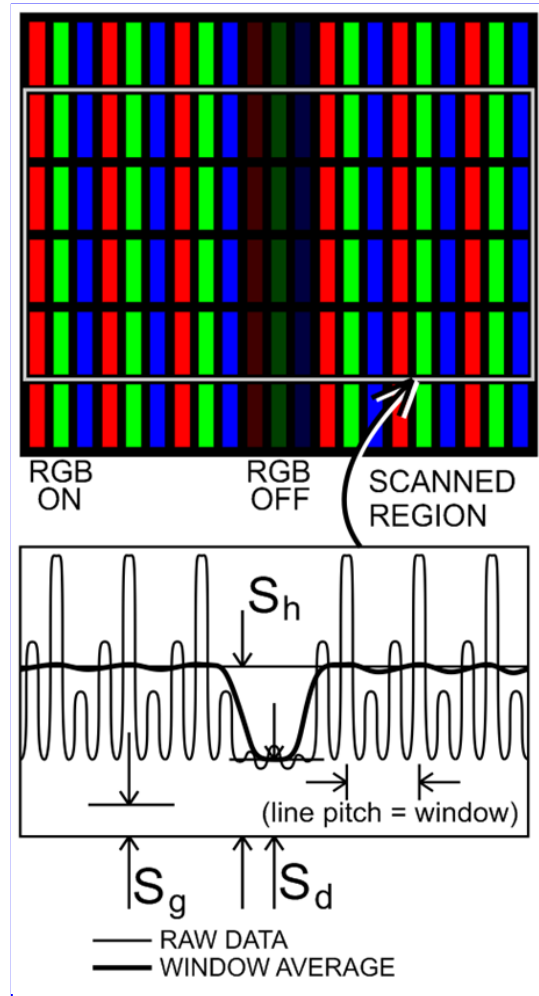


OTHER SETUP CONDITIONS: Equipment: Scanning or array LMD. Test pattern: single vertical line generated near center screen. Generate a single-pixel-wide vertical black line near the center of an otherwise white screen in an appropriate signal-pixel pattern and present it to the DUT. Arrange to scan two, four, six or more horizontal lines in pairs (the figure shows four lines being scanned). The LMD must be linear and provide a luminance profile orthogonal to the line (either directly in its output or via an RGB to tristimulus transformation). The LMD need not be calibrated in cd/m^2 unless a luminance value is required rather than relative luminances.

PROCEDURE: With an array or scanning LMD, obtain the luminance profile of the vertical black-pixel line and the white region. Obtain the net signal S as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made (see A2 Stray-Light Management & Veiling Glare for proper procedures). See the figure for an illustration of the pixel configuration and data.

ANALYSIS: Perform a running window average (moving-window-average filter, see B18 for details) of the luminance profile where the averaging window width w is equal to the line width. There should be at least 20 or more detector pixels per line width, if possible. For example, if an array detector is used, and with the magnification of the imaging lens there are 53 array pixels which cover the DUT line width, then the running average window width is 53 array pixels wide. From the resulting moving-window-average profile determine (1) the net level of the vertical black line $S_K = S_d - S_g$, where S_d is the minimum (“d” for dim) of the profile and S_g is the glare corruption of the image and black line, and (2) the net level of the white area on the sides of the black line $S_W = S_h - S_g$, where S_h is the average level (“h” for high) of the white area of the profile. Compute the small area contrast for the character or stroke. In summary:

WARNING
This measurement can be grossly inaccurate unless proper accounting (and/or correction) is made for veiling glare (A2).





$$\begin{aligned}
 S_K &= S_d - S_g \\
 S_W &= S_h - S_g \\
 C_L &= S_W / S_K, \text{ where } \left\{ \begin{array}{l} S_g = \text{glare correction} \\ S_h = \text{white level (high)} \\ S_d = \text{black level (dim)} \\ S_W = \text{net white value} \\ S_K = \text{net black value} \\ C_L = \text{line contrast} \\ C_M = \text{Michelson contrast} \end{array} \right. \\
 C_M &= \frac{S_W - S_K}{S_W + S_K}
 \end{aligned}$$

REPORTING: Report the line contrasts to no more than three significant figures. It also may be useful to report the values of the glare correction, net white, and net black signals.

COMMENTS: Note: (1) In this measurement a horizontal line can be used, or perhaps a measurement of both vertical and horizontal lines will be desired. The procedure is the same for horizontal lines as for vertical lines; Additionally, if it is desired to measure the luminance or contrast of a white line on a black screen (negative configuration), the same procedure can be used with “black” and “white” switched around. (2) If the window width w cannot be readily determined, you can use § 7.2 Grille Luminance and Contrast with a 1×1 grille to determine w . If the display uses subpixel rendering to define the line, it may be possible to determine the window width from the subpixel structure. (3) A black line on white is described here. Gray shades (or colors) may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis Example

Glare: S_g	1772
High: S_h	9331
Dim: S_d	4239
$S_W = S_h - S_g$	7559
$S_K = S_d - S_g$	2467
$C_L = S_W / S_K$	3.1
C_M	0.426

—SAMPLE DATA ONLY—

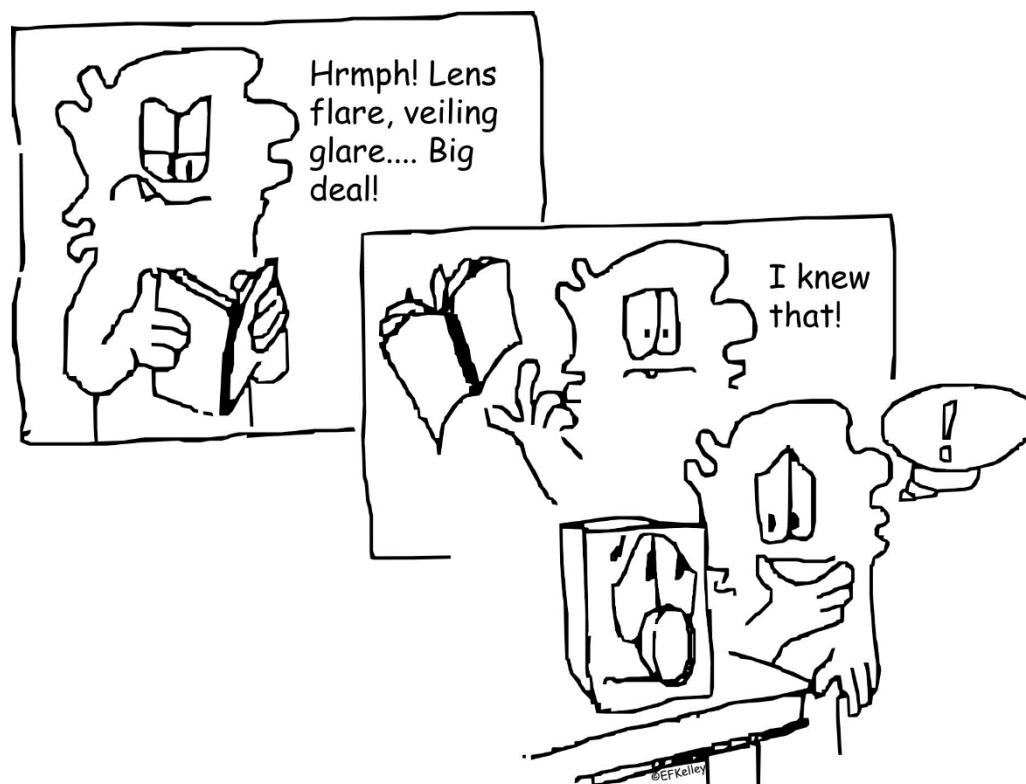
Do not use any values shown to represent expected results of your measurements.

Reporting Examples

S_g	1772
S_W	7559
S_K	2467
C_L	3.1
C_M	0.426

SPATIAL

SPATIAL





7.2 GRILLE LUMINANCE & CONTRAST

ALIAS: N×N grille luminance & contrast

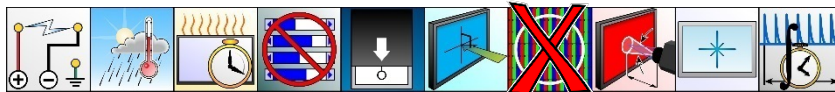
DESCRIPTION: Measure the small area luminances at the center of the screen of horizontal and vertical grille test patterns consisting of alternating white and black horizontal or vertical lines covering the entire screen. Calculate the contrast ratio obtained (or other suitable contrast metric) for the moving-window average of the luminance profile based upon the observed line width. **Units:** cd/m² if absolute luminance is needed, none for contrast (a ratio). **Symbol:** C_g (optionally C_M)

The difficulty is to accurately determine the luminance of the black line L_K between white lines L_W of the same width without corruption from, for example, the lens system of the LMD or reflections between the LMD and the FPD. We call for the contrast ratio $C_g = L_W/L_K$, here and especially the Michelson contrast $C_M = (L_W - L_K)/(L_W + L_K)$. An $n \times n$ grille pattern is either horizontal or vertical alternating white and black lines each having a width of n signal pixels. It is important in such measurements to attempt to account for any contrast-reducing glare (veiling glare) in the measurement system. One use of C_M is found in § 7.8 Resolution from Contrast Modulation in determining a realistic resolution for a display.

Note: Black and white lines are described here. Gray shades may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes. Colored grilles are discussed in 7.2.1.

WARNING

This measurement can be grossly inaccurate unless proper accounting (and/or correction) is made for veiling glare (A2).



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

—SAMPLE DATA ONLY—

Do not use any values shown in this section to represent expected results of your measurements.

OTHER SETUP CONDITIONS: Alternatively exhibit a horizontal grille and then a vertical grille test pattern and arrange for a spatially resolving LMD to measure the luminance profiles at screen center. A correction must be made for veiling glare (see the appendix A2 Stray-Light Management & Veiling Glare). Arrange to measure two, four, six or more rows (or columns) in pairs—we recommend four to six. Figure 1 shows four lines being averaged.

PROCEDURE & ANALYSIS: With an array or scanning LMD, measure luminance profiles for both horizontal and vertical grille patterns. Obtain the net signal S as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made wherever possible (see A2 Stray-Light Management & Veiling Glare). See Figure 1 for an illustration of the pixel configuration and data. Because of the complications that can be involved in making this measurement (in particular, determining the line width), we discuss the procedure in great detail in the following for both simple RGB pixels and subpixel rendering of the lines:

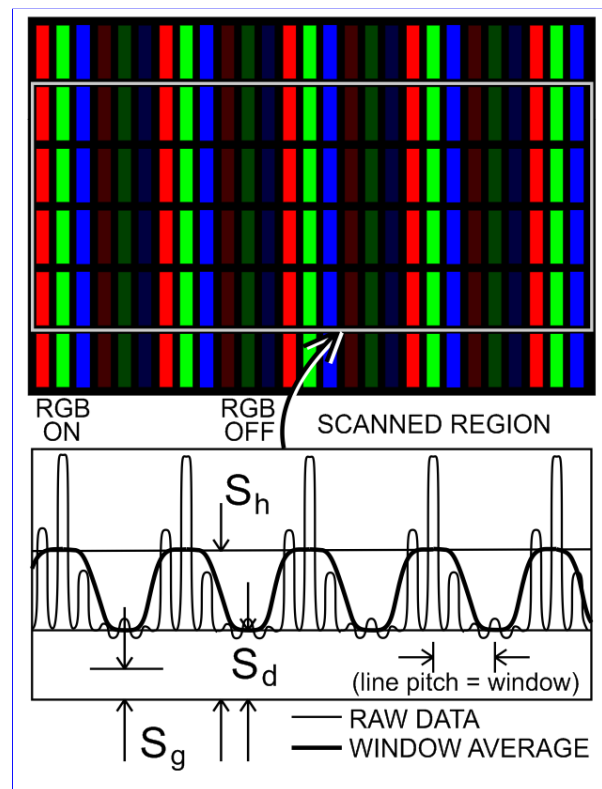


Fig 1. Parameters associated with a moving-window average of the grille luminance profile.



We discuss signal pixels, display pixels, and subpixels in what follows. We have signal pixels (spx) that tell or command the display what to show and where. We also have camera or imager pixels (cpx) that record imagery appearing on the display surface. Some displays have physical pixels (px) that are repeating groups of subpixels, and some displays have logical pixels (lpx) that reproduce what the signal pixel commands but can use a number of the surrounding subpixels to form the proper color. This is done because the colors, particularly red and blue, are less resolved by the eyes compared to the white at the luminance levels of those colors. Some displays don't have pixels as we've defined them here, but they do have subpixels; PenTile® displays can be like this. Thus, there are now and are coming a variety of new display technologies. The reason for this extensive procedure is to help people understand how to apply the ideas and the intent of this method so they can correctly measure the grille contrasts of these newer technologies. Please see the introductory comments at the beginning of this chapter under the heading: Pixels and Subpixel Rendering for Resolution Measurements.

1. **Grille Pattern:** Apply a grille test pattern to generate an array of dark and bright lines (a black and white grille) in horizontal or vertical direction with minimal grille periodicity (i.e. as narrow as possible or matching the manufacturer's claimed resolution)—see Figures 2 and 3. Make sure the bright lines do not show any visible color changes along their length.

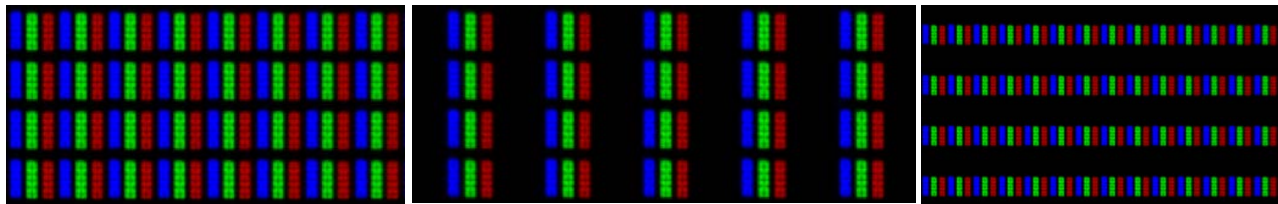


Figure 2. Example of a square-pixel RGB display showing the subpixel configuration for white (left), for the vertical 1×1 grille (center), and for the horizontal 1×1 grille (right). It was for such a display that Sections 7.2 and 7.8, in fact, the entire chapter, were originally written. Now things can be more complicated.

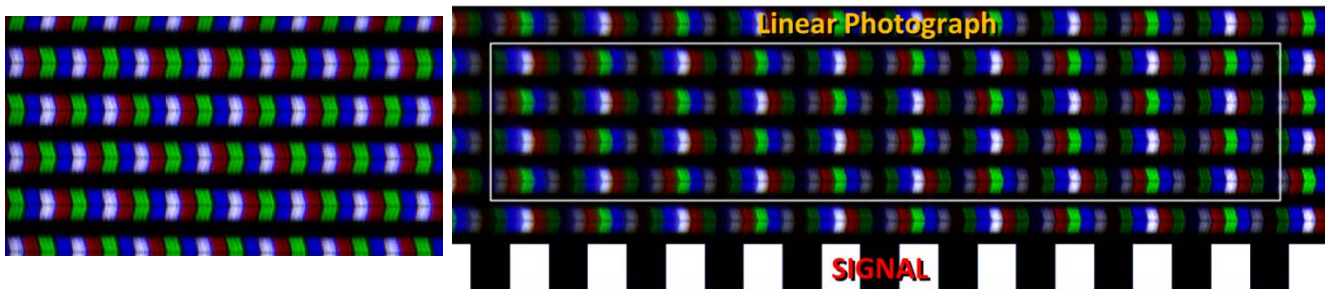


Figure 3. Example of an RGBW display with each consecutive line shifted by two subpixels (left picture). The 1×1 vertical grille is displayed in the right picture where the locations of the white lines are on the even lines of the signal pixel (or if the grille were covering the entire width of the screen, the first black line would be at the left edge of the screen). The box indicates the region used in calculating the moving-window average (MWA). Although more than three subpixels are involved in reproducing the white lines, the width of the window for the MWA is equivalent to the width dictated by the signal, or three subpixels in this case. The width of the window doesn't change because the display renders the lines wider than the signal would dictate; otherwise the width of the black lines would be too small. The MWA is intended to combine the subpixels into an equivalent of one pixel or to approximately simulate what the eye sees at the optimal viewing distance where the average line width subtends 1 arcmin. That width is based upon what the signal commands and not how the display renders the line. The key point is: How well the display renders the line is shown after the MWA is determined and is indicated by the Michelson contrast of the MWA of the grille.

2. **Grille Image :** Measure the relative luminance distribution of the grille pattern with an imaging photometer (imaging light measurement device, ILMD) if possible, or a common RGB camera might be used—see Figures 2 and 3.
 - a. The spatial sampling rate should be above 10 per subpixel (i.e. more than 10 ILMD detector elements per subpixel of the display). (If the display does not have subpixels then try to capture the grille lines with 30 or more camera pixels [cpx].)
 - b. When a display has more than three RGB subpixels of other colors, the common commercial camera may not be adequate to properly render the grille into an accurate luminance image or profile. That is, a transformation may not exist that can adequately transform the camera's three RGB pixels into correct tristimulus values (X,Y,Z) arising from the display having more than three RGB subpixels, e.g., RGBY, RGBW, RGBC, etc. If an adequate



transformation cannot be established, then a good photopic or tristimulus imager may be required to obtain an accurate luminance profile. See Appendix A16 Color Transformations: RGB to XYZ for more details.

3. **Camera or Imager Considerations:** Obtaining a good quality image of the grille is essential to the success of this measurement. Accurate luminance measurements require detector calibration, but the calculation of contrasts (ratio of luminances) does not require an accurate luminance calibration. They only require linear relative luminance results. Here are a number of considerations:
 - a. Stray light issues may be resolved with replica masks (see IDMS A2.1.6). There may also be reflections from the camera lens to consider when the camera lens is close to the display surface (as it usually is in order to make high-magnification images). For example, if 2% of the light is reflected back to the display and the surface of the display has a specular reflectance of 4%, then the proximity of the lens may account for an addition of 0.08% of the light.
 - b. Make sure the display pixel-matrix is aligned parallel-normal to the detector matrix of the ILMD as best as possible. Small rotational corrections might be able to be made in software to better align the image with the detector pixel matrix.
 - c. The ILMD output should be corrected for its dark signal (background subtraction).
 - d. A flat-field correction may also be necessary if more than the central region of the image is being used for measurement purposes. This can have to do with the $1/\cos^4(\theta)$ fall-off associated with the lens (see B13 in the appendix).
 - e. The image should be focused as best as possible. Using too large of an f-stop (too small a lens opening) may diffuse the image too much. If the lens has an adjustable aperture, there is usually an optimum opening that provides the sharpest images (often this is one or two f-stops down from open).
 - f. Avoid irregularities from screen refresh problems. Lowering the speed (ISO speed or sensitivity) and extending the exposure can help with this. If practical, set the camera exposure time to an exact multiple of the display refresh period or $4\times$ the display refresh period if temporal dithering/modulation is used by the display to achieve intermediate drive levels.
 - g. Watch for lens distortions like barrel or pincushion. Also avoid nonuniform areas of the screen and any failed pixels.
 - h. Be careful to avoid saturating the detector pixels. (This will often require the image to appear dark.)
 - i. The camera or imager must be linear in its response to light. For common cameras this will be the raw output from the camera.
 - j. Tests should be performed at some point to be sure to establish the range over which the ILMD is linear. Often when near a detector-pixel saturation condition you may find some nonlinearity.
 - k. If using an RGB camera, the RGB levels must be transformed to tristimulus values whereby the luminance is obtained. See Appendix A16 Color Transformations: RGB to XYZ for more details.
4. **Luminance Profile:** Obtain a relative luminance profile orthogonal to the grille line direction from the luminance image by averaging along the direction of the grille (i.e. apply vertical averaging in order to obtain horizontal profiles and vice versa)—see Figure 4 where the luminance is measured in camera counts (uncalibrated) via an RGB transformation.
 - a. Try to average over four or more orthogonal lines (horizontal lines in the case of Figure 3) to obtain a good representation of the bright and dark lines and reduce noise.
 - b. Start and stop the averaging along the lines at the center of the thin black region between the subpixels to obtain the correct contribution of the black level to the average.
 - c. If each consecutive line (usually horizontal) is shifted, then use two or more pairs of lines to obtain a good average to represent the content equally of each line.

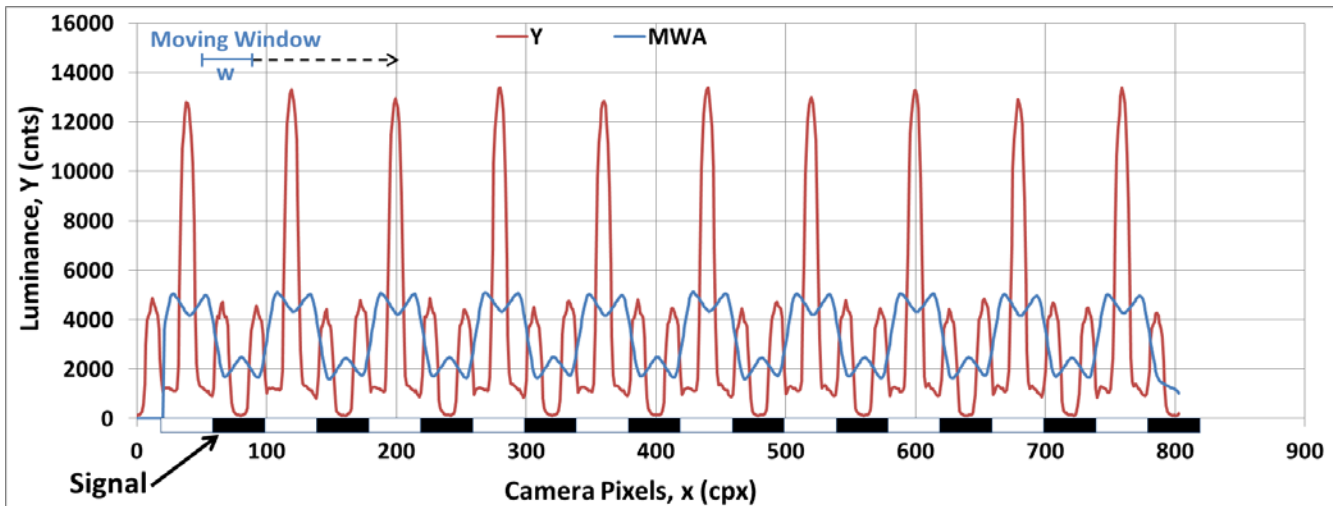


Figure 4. The luminance profile (integration along the vertical grille lines) of Figure 3 shown in red. The moving-window average is shown in blue.

5. **Window Width:** Evaluate the periodicity of the luminance profile by simply counting the ILMD detector elements (cpx) over a range of grille lines for determination of the line (column) width and window width—see Figure 5.
 - a. Do not attempt to count subpixels for the line width (and window) measurement!
 - b. Determine the number of detector pixels from one peak P_{start} (in cpx) to another peak P_{end} from five to ten peaks away. Divide that range $\Delta x = P_{\text{end}} - P_{\text{start}}$ by the number of lines N covered by that range (two lines, black and white, between peaks) to obtain the width $w = \Delta x / N$ for the MWA, which is also the average line width for the 1×1 grille.
6. **Moving-Window Average:** Perform the MWA using w over the entire selected luminance profile as in Figure 4.
 - a. If the window w is not an integer (as it rarely is), you can perform the MWA with $\text{int}(w)$ and then another MWA with $\text{int}(w)+1$ and interpolate the results for the actual width w .

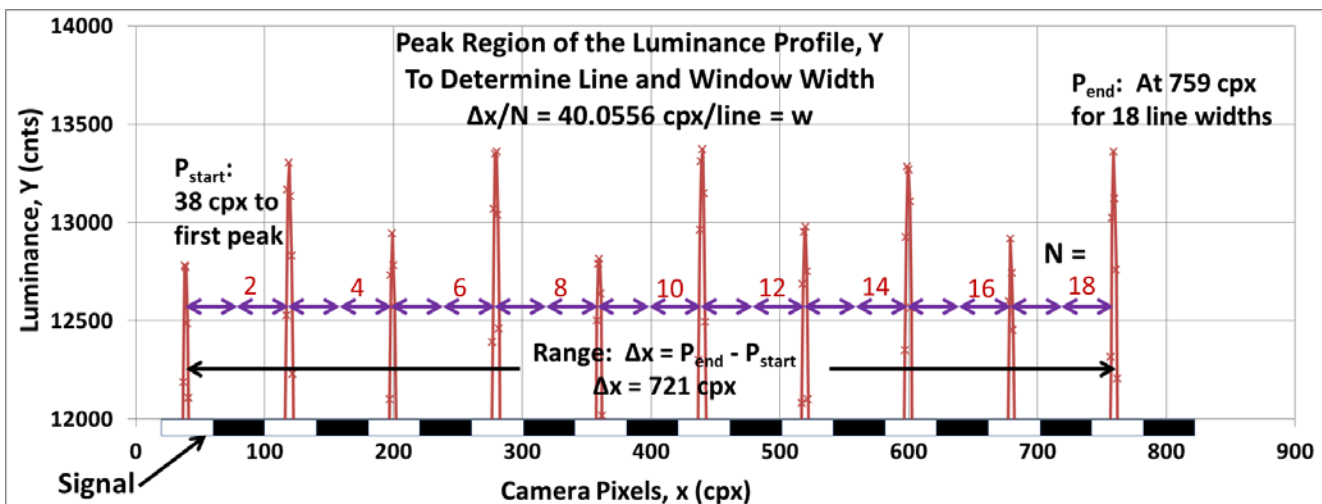


Figure 5. Peak region of the luminance profile. By measuring the distance between widely separated peaks and dividing by the number of lines that can be contained in that distance we can obtain an accurate value for the window width w , which is the same as the average line width.

7. **Luminance Extrema:** Determine the individual levels of maxima and minima of the MWA profile and calculate an average value for all maxima and for all minima for five to ten maxima and minima.
8. **Michelson Contrast:** Determine the Michelson contrast from the average values of the maxima and minima and report the result in percent to no more than two significant figures.
9. **Phase of Grille:** Check to see if by changing the phase of the grille, from black-white repeated to white-black repeated, the rendering of the grille is changed. If the grille changes depending upon the phase, then you must remeasure the grille using the above procedure for the new phase—see Figures 6, 7, and 8. If the Michelson contrast is phase dependent, report both phase results and the average of the two. Numbering the lines starting at one from the top or left of the



screen, the phase is odd if the bright line is found on odd numbered lines (rows or columns) and “even” if found on even numbered lines.

10. **Larger-Width Grilles:** For larger-width grilles, 2×2 , 3×3 , and so forth, in performing the MWA we use the same window width w that comes from the 1×1 analysis. The window width w used in the MWA for wider grille lines than 1 spx is not equal to the average line width of the wider grille lines. If the window width cannot be determined from a 1×1 grille then use the window width divided by two that would be determined from a 2×2 grille, and so on: For an $n \times n$ grille, the window width $W = w_n / n$, where w_n is the width of the line for the $n \times n$ grille.

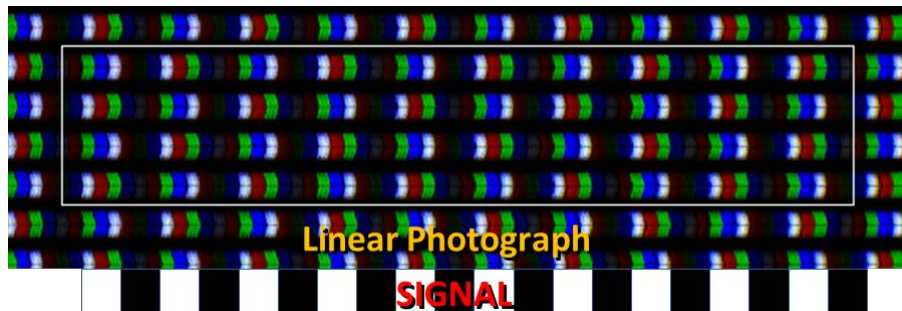


Figure 6. Example of a phase-shifted grille on an RGBW display where the white line is on the odd lines of the signal (or if the grille were covering the entire width of the screen, the first white line would be at the left edge of the screen).

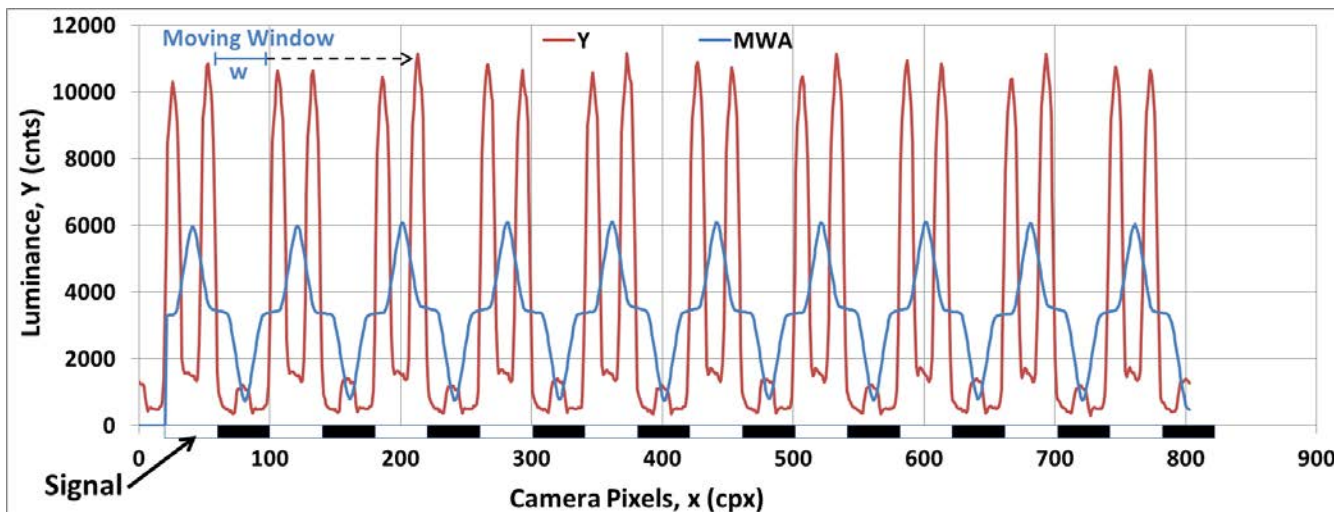


Figure 7. Luminance modulation and MWA of the phase-shifted grille in Figure 6. Note the double peaks for each white line.

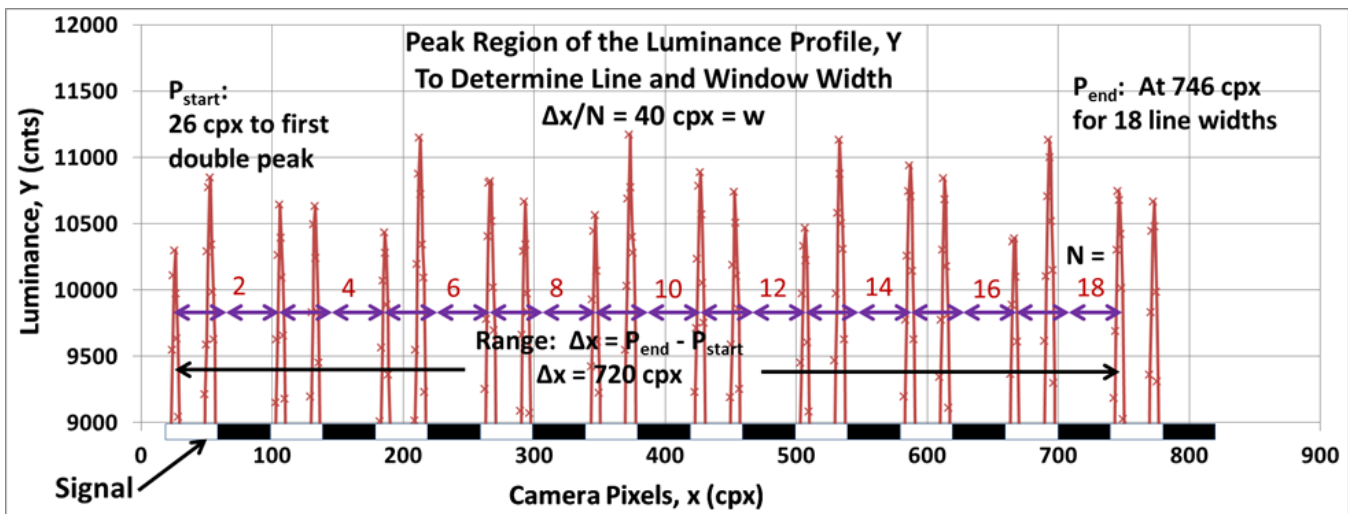


Figure 8. Determination of MWA window width based upon identifying the same location of the peak at each line position in the phase-shifted grille.

Summary: Perform a running average (moving-window-average filter, see B18 for details) of each luminance profile where the averaging window width is the width of the line as rendered from the signal pixels. There should be at least 10 or more detector pixels per display line width, if possible, try for 30 or more. See Figure 1: From the resulting modulation curve determine (1) the net level of the grille black lines $S_K = S_d - S_g$, where S_d is the minimum of the grille black lines and S_g is the correction for glare or stray light, and (2) the net level of the grille white lines between the specified black lines $S_W = S_h - S_g$, where S_h is the average maximum of the grille white lines. Compute the grille contrast ratio $C_g = S_W/S_K$ for horizontal and for vertical grille patterns. In summary:

$$\begin{aligned}
 S_W &= S_h - S_g \\
 S_K &= S_d - S_g \\
 C_g &= S_W / S_K \quad , \quad \text{where} \\
 C_M &= \frac{S_W - S_K}{S_W + S_K}
 \end{aligned}
 \quad \left\{ \begin{array}{l}
 S_g = \text{glare correction} \\
 S_h = \text{white line average (high)} \\
 S_d = \text{black line average (dim)} \\
 S_W = \text{net white value} \\
 S_K = \text{net black value} \\
 C_g = \text{grille contrast} \\
 C_M = \text{Michelson contrast or contrast modulation}
 \end{array} \right.$$

The sample data shown here are net CCD counts from a photopic camera. The CCD counts S are only proportional to the luminance values.

REPORTING: Report the grille contrast ratio C_g as a number to no more than three significant figures. Also report the type of grille pattern used. It is suggested that the mask, net white, and net black signals be presented as well. The luminance of the white and black lines may be reported if the device is properly calibrated for absolute luminance measurements.

COMMENTS: Grille contrast ratio measurements are required for the determination of true resolution because spatial resolution capabilities of the DUT may or may not be closely correlated with the addressability. The contrast ratio of a display is very sensitive to an accurate black measurement and any veiling glare contribution.

ADDITIONAL COMMENTS: (1) **Measurement Locations:** The location at center screen may not be an important requirement. Near center or in other locations of convenience can be used if the contrast does not depend upon the location. Often a visual inspection of the grilles at various locations will assure you of consistency.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis (Sample Data)

Orientation	Ver.
Grille	1 x 1
Glare: S_g	1772
High: S_h	7559
Dim: S_d	2467
$S_W = S_h - S_g$	5787
$S_K = S_d - S_g$	695
$C_g = S_W / S_K$	8.3
C_M	0.786
Orientation	Hor.
Grille	2 x 2
Glare: S_g	1342
High: S_h	7623
Dim: S_d	1983
S_W	6281
S_K	641
C_g	9.8
C_M	0.814

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting Results - Sample Data

	Horizontal Grille (cd/m ²)	Vertical Grille (cd/m ²)
Grille Contrasts		
Grille type:	2 x 2	2 x 2
C_g	3.1	2.3
C_M	0.786	0.814
L_W	13.8	9.82
L_K	4.45	4.41
L_{ave}	9.13	7.12



(2) Thresholds and Uncertainty: There can be target thresholds for these measurement results such as described in § 7.8. These are often used as a pass-fail test. Whenever the results get close to the threshold, the uncertainty of the measurement becomes important. A display cannot be rejected or approved in meeting the desired threshold when the measurement result is closer to that threshold than the measurement uncertainty of the measuring system. For example, if the measurement uncertainty of your apparatus (instrumental and procedural) is 5 % the evaluated luminance modulation must be >55% for a sure pass and <45% for a sure fail (reject). Results between 45% and 55% would be too uncertain to trust. Although any LMD or imaging LMD (ILMD) is usually limited to from 2% to 4% absolute measurement uncertainty, because the Michelson contrast is a ratio of two such measurements, this overall uncertainty can divide out. The uncertainties that corrupt the Michelson contrast measurements are detector nonlinearity, lens imperfections, veiling glare, edge reproduction by the lens, imperfect color transformations, tristimulus filtration errors, and other things (see Section 7.2 in the Addendum under 3. Camera or Imager Considerations). A 1% uncertainty is *VERY* hard to achieve. We are not talking about repeatability here; we are discussing the uncertainty (see the Appendix B21 Statements of Uncertainty).

(3) Reporting Michelson Contrasts Using Thresholds: When thresholds are used for a pass-fail test, it is mandatory that the Michelson contrast obtained for the 1×1 grille also be reported. For example, suppose a near-eye display advertises a resolution of 1920×1080 and the horizontal 1×1 grille using § 7.8 is found to have a Michelson contrast of 76%, then the manufacturer must report that the resolution as “1920 lines at $C_m = 76\%$ ” or something similar to report the Michelson contrast of the 1×1 grille. (We realize that making a mandatory requirement of reporting the contrast can be viewed as a departure from the general philosophy of this document as noted in the abstract on the title page and in the Introduction. However, we also wish to avoid the lack of a measurement result that the pass/fail thresholds can introduce; thus, we want to be sure that the measurement result is also available to all.)

(4) Grille Phases: When the Michelson contrast of the grille is phase dependent, then the average of the two phases may be reported provided that both contrasts for each phase are also reported.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Sample Data Fig. 1		Sample Data Fig. 2		Sample Data Fig. 5	
Orientation	<i>Vertical</i>	Orientation	<i>Vertical</i>	Orientation	<i>Vertical</i>
Phase	<i>NA</i>	Phase	<i>even</i>	Phase	<i>odd</i>
Grille	<i>1 x 1</i>	Grille	<i>1 x 1</i>	Grille	<i>1 x 1</i>
Window, w (cpx)	<i>37.111</i>	Window, w (cpx)	<i>40.056</i>	Window, w (cpx)	<i>40</i>
$C_M(\text{int}(w))$	<i>0.9607</i>	$C_M(\text{int}(w))$	<i>0.4964</i>	$C_M(\text{int}(w))$	<i>0.7749</i>
$C_M(\text{int}(w)+1)$	<i>0.9545</i>	$C_M(\text{int}(w)+1)$	<i>0.4470</i>	$C_M(\text{int}(w)+1)$	<i>NA</i>
Interpolated C_M	<i>0.9600</i>	Interpolated C_M	<i>0.4964</i>	Interpolated C_M	<i>0.7749</i>
Reported C_M	<i>96%</i>	Reported C_M	<i>50%</i>	Reported C_M	<i>77%</i>
		Average C_M		<i>64%</i>	



7.2.1 COLORED GRILLE LUMINANCE & CONTRAST

ALIAS: Color discernment

DESCRIPTION: Measure the small area luminances at the center of the screen of horizontal and vertical grille test patterns consisting of alternating primary-color and black horizontal or vertical lines covering the entire screen. Calculate the contrast ratio obtained (or other suitable contrast metric). Use the method described in § 7.2 Grille Luminance and Contrast. Other colors than the primary colors may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes. **Units:** cd/m² if absolute luminance is needed, none for contrast (a ratio). **Symbol:** C_g (optionally C_M)

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Same as § 7.2 but using colored grilles.

PROCEDURE & ANALYSIS:

Follow the procedure and analysis in § 7.2 Grille Luminance and Contrast.

—SAMPLE DATA ONLY—
Do not use any values shown in this section to represent expected results of your measurements.

REPORTING: Although the results of this measurement could be focused on only a particular color or several colors, usually people will be interested in a full report of the 1×1 grilles (on black) of primary colors and white.

The table below provides an example of a complete report. That table may also be summarized by the following statement:

3840×2160: $C_{MW} = 0.41$ H × 0.45 V, $C_{MR} = 0.44$ H × 0.49 V, $C_{MG} = 0.45$ H × 0.45 V, $C_{MB} = 0.41$ H × 0.40 V.

Here, H, V, W, R, G, and B stand for horizontal, vertical, white, red, green, and blue respectively. Another way to describe these results might be:

3840 white-black 1×1 horizontal grille with

$C_{MWH} = 0.62$.

2160 white-black 1×1 vertical grille with $C_{MWV} = 0.56$.

Resolution with $C_M = (C_{MWH} + C_{MWV})/2 = 0.59$

3840 red-black 1×1 horizontal grille with $C_{MRH} = 0.64$.

2160 red-black 1×1 vertical grille with $C_{MRV} = 0.62$.

Red discernment $C_{MR} = (C_{MRH} + C_{MRV})/2 = 0.63$.

3840 green-black 1×1 horizontal grille with $C_{MGH} = 0.68$.

2160 green-black 1×1 vertical grille with $C_{MGV} = 0.62$.

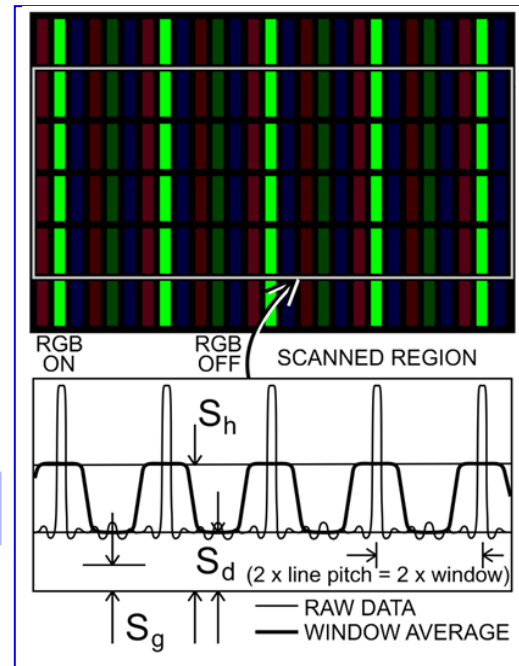
Green discernment $C_{MR} = (C_{MRH} + C_{MRV})/2 = 0.65$.

3840 blue-black 1×1 horizontal grille with $C_{MRH} = 0.58$.

2160 blue-black 1×1 vertical grille with $C_{MRV} = 0.56$.

Blue discernment $C_{MR} = (C_{MRH} + C_{MRV})/2 = 0.57$.

COMMENTS: None.



Target Resolution 3840x2160				
Color	Contrast Modulation	Odd Grille	Even Grille	Average
<i>Horizontal 1×1 grille (color on black) indicating vertical resolution (for white on black grilles) or color discernment (for color on black grilles):</i>				
White	$C_{MWH} 1 \times 1$	0.39	0.43	0.41
Red	$C_{MRH} 1 \times 1$	0.42	0.46	0.44
Green	$C_{MGH} 1 \times 1$	0.48	0.42	0.45
Blue	$C_{MBH} 1 \times 1$	0.44	0.38	0.41
<i>Vertical 1×1 grille (color on black) indicating horizontal resolution (for white on black grilles) or color discernment (for color on black grilles):</i>				
White	$C_{MWV} 1 \times 1$	0.43	0.47	0.45
Red	$C_{MRV} 1 \times 1$	0.48	0.50	0.49
Green	$C_{MGV} 1 \times 1$	0.46	0.44	0.45
Blue	$C_{MBV} 1 \times 1$	0.44	0.36	0.40



7.3 INTRACHARACTER LUMINANCE & CONTRAST

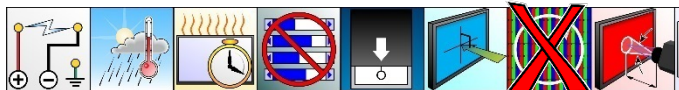
ALIAS: ($m \times n \times q \dots$ grille contrast ratio)

DESCRIPTION: Measure the small area luminances at the center of the screen of horizontal and vertical grille test patterns consisting of alternating white and black horizontal or vertical lines of various widths covering the entire screen. Calculate the contrast ratio obtained (or other suitable contrast metric). **Units:** cd/m^2 if absolute luminance is needed, none for contrast (a ratio).

Symbol: C_g (optionally C_M)

This is an extension of the $n \times n$ grille contrast ratio (§ 7.2). An $m \times n \times m \times q$ grille is either horizontal or vertical alternating white and black lines in a repeating pattern of black and white lines that can be different widths. The region of interest is usually the regions where the lines are closest together and not the white area separating the groups. **Note:** Black and white are described here. Gray shades (or colors) may also be used provided all interested parties are in agreement and all reporting documentation clearly describes any changes.

SETUP: As defined by these icons, standard setup details



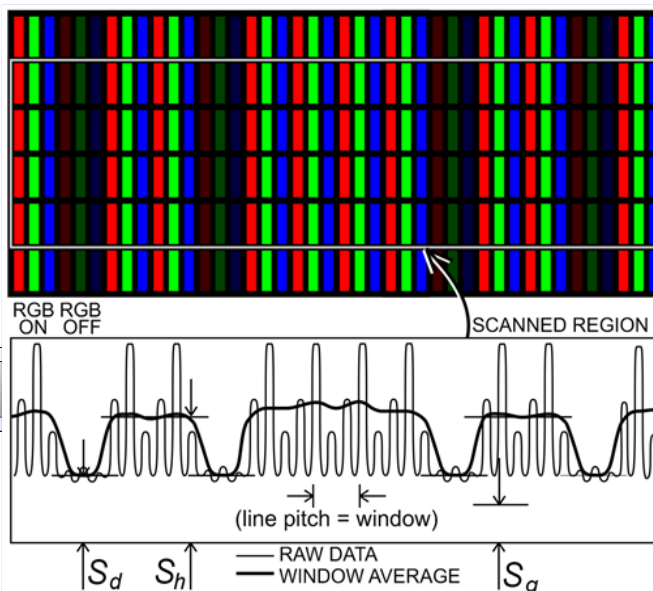
apply (§ 3.2).

OTHER SETUP CONDITIONS: Alternatively display a horizontal grille (if required) and then a vertical grille test pattern and arrange for a spatially resolving LMD to measure the luminance profiles at screen center. A correction must be made for veiling glare (see A2 Stray-Light Management & Veiling Glare). Arrange to measure an integral number of rows (or columns). The grille that is required depends upon the people involved and the application. It must be negotiated by all interested parties. Equipment: Scanning or array LMD. Test pattern: horizontal grille, vertical grille (repeating on/off line pattern).

PROCEDURE: With an array or scanning LMD, measure luminance profiles for both horizontal and vertical grille patterns subject to above setup conditions. Obtain the net signal S as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made (see A2 Stray-Light Management & Veiling Glare for proper procedures). See the figure for an illustration of the pixel configuration and data.

WARNING

This measurement can be grossly inaccurate unless proper accounting (and/or correction) is made for veiling glare (A2).



—SAMPLE DATA ONLY—

Do not use any values shown in this section to represent expected results of your measurements.



ANALYSIS: Perform a running window average (moving-window-average filter, see A18 for details) of the luminance profile where the averaging window width is as close as possible to the width of a single-signal-pixel line as rendered by the LMD. For an array detector this is however many detector array pixels are needed to cover one display pixel. There should be at least 10 or more detector pixels per display subpixel, if possible. From the resulting modulation curve determine (1) the net level of the grille black line $S_b = S_d - S_g$, where S_d is the minimum of the grille black lines, and (2) the net level of the grille white line $S_w = S_h - S_g$, where S_h is the average maximum of the grille white lines. Compute the small area contrast ratio $C_g = S_w/S_b$ for horizontal and for vertical grille patterns. In summary:

$$\begin{aligned}
 S_w &= S_h - S_g \\
 S_K &= S_d - S_g \\
 C_g &= S_w / S_K \quad , \quad \text{where} \\
 C_M &= \frac{S_w - S_K}{S_w + S_K}
 \end{aligned}
 \quad
 \begin{cases}
 S_g = \text{glare correction} \\
 S_h = \text{white line average (high)} \\
 S_d = \text{black line average (dim)} \\
 S_w = \text{net white value} \\
 S_K = \text{net black value} \\
 C_g = \text{grille contrast} \\
 C_M = \text{Michelson contrast or contrast modulation}
 \end{cases}$$

REPORTING: Report the grille contrast ratio C_g as a number to no more than three significant figures. Also report the type of grille pattern used. It is suggested that the mask, net white, and net black signals be presented as well. If luminance levels are required, then the camera must be calibrated in cd/m^2 for absolute measurements.

COMMENTS: The contrast ratio of a display is very sensitive to an accurate black measurement, see Uncertainty Evaluations (A10) in the Metrology Appendix. There may be complications associated with making small area contrast measurements, see A2 Stray-Light Management & Veiling Glare.

The purpose of the $m \times n \times q...$ grille measurement is to approximate the contrast found with a character. When measuring the character contrast, the height of the character can influence the value of the black measured because of glare (at the very least). If glare is going to be measured by using a replica mask, making a mask the same size and shape of the character would be very difficult. It is much easier to produce an opaque black replica mask of a line than a character. The black measured on a character can change depending upon where the black is measured, the measurement of lines provides a more reproducible measurement. The reason for the $m \times n \times q...$ grille is to simulate a character like a small “m” where the distance between the legs of the “m” might be two pixels and the leg width might be one pixel, but there may be three or more pixels separating the characters. Thus a $1 \times 2 \times 1 \times 2 \times 1 \times 4$ grille might adequately simulate the “m” for this example.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis Example

Orientation	Ver.
Grille	$1 \times 2 \times 4$
Mask: S_g	1772
White: S_h	7559
Black: S_d	2467
S_w	5787
S_K	695
C_g	3.8
Orientation	Hor.
Grille	$2 \times 3 \times 5$
Mask: S_g	1653
White: S_h	7489
Black: S_d	2217
S_w	5836
S_K	564
C_g	10.3

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting Results - Example

Grille Contrasts	Horizontal Grille	Vertical Grille
Grille type:	$2 \times 3 \times 5$	$1 \times 2 \times 4$
C_g	10.3	3.8



Yes, I know this is late. ...
 Yes, ... Please remove those three paragraphs.
 ... But it is important! ...
 But. ... I may get FIRED!
 ... Well, can you go get it back from the printers?
 ... You know, you're doing a great job with editing this thing....



7.4 PIXEL FILL FACTOR

DESCRIPTION: We measure the pixel fill factor using an area LMD or calculate it based on design parameters.

The pixel fill factor is the amount of the area producing useful luminance compared to the amount of the area allocated to the pixel. Fill factors that are not 100 % can influence display quality from an ergonomic standpoint.

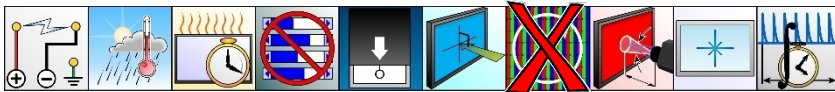
Note that some displays have well-defined pixels because of a known black matrix. In such cases the pixel fill factor may be calculated from geometry.

In the example at the right, what might be a typical TFT LCD subpixel arrangement, a 60H × 50V array detector measures a single pixel. The pixel size is 46 × 46 or 2116 detector pixels, the red, green, and blue subpixels are each covered by 420 detector pixels. The fill factor is

$$f = \frac{420 + 420 + 420}{2116} = 0.595 \text{ or } 60\%$$

In what follows we refer to subpixels for the case of color displays. Should a monochrome display be measured, read “pixel” instead of “subpixel.”

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: If the subpixels are relatively uniform ($\pm 20\%$ of average luminance) and well-defined (sharp edges visible where the average luminance of the subpixel is attained from the black surround within a distance of 10 % of the smallest horizontal width or height of the subpixel), then it is possible to calculate the fill factor if the pixel design parameters are known or can readily be measured. If the pixels are not uniform in luminance cross-section, arrange for either a scanning or array LMD to measure the area luminance of the subpixels over the entire area of at least one typical pixel. Equipment: Scanning or array LMD. White full screen.

PROCEDURE & ANALYSIS:

Well-Defined Subpixels: For many display technologies the subpixel matrix mask and resulting pixels are well-defined and relatively uniform (say $\pm 20\%$ of the average luminance). In such a case, the fill factor can be calculated from geometry if the design spatial parameters are known, or it may be calculated by measuring the sizes of the subpixels: Sum up the area of the subpixels $s = s_R + s_G + s_B$ and divide by the area allocated to the pixel $a = P_H P_V$, where s_i is the area of each subpixel, P_H is the pixel pitch in the horizontal direction, and P_V is the pixel pitch in the vertical direction. The fill factor is $f = s/a$.

Non-Uniform Subpixels: With other technologies where the subpixel is not uniform in its cross-section as viewed, a spatially resolved LMD must be used to measure the luminance distribution of each subpixel. The LMD need not be calibrated in units of luminance, but it should be linear over the range of luminances measured. Using a white screen, select one pixel near the center of the screen that appears to be typical ($\pm 10\%$ of average in the center region). For each subpixel i within that pixel determine the peak subpixel level S_i . Locate the darkest detector pixel in the near vicinity of the selected pixel (such as within the black matrix mask that separates the subpixels or within some other available structure that is black) then determine the minimum of the black area (its dimness) S_d . This dimness value includes the true black value S_K and any additional glare S_g so that $S_d = S_K + S_g$. We will call the measured luminance of any detector pixel within the subpixel $S_i(x,y)$, where (x,y) denotes the location of the detector pixel. The net luminance of each detector pixel within any subpixel is then the measured luminance with the true black value and the glare subtracted

$K_i(x,y) = S_i(x,y) - S_g - S_K = S_i(x,y) - S_d$. The net maximum luminance is given by $S_i - S_g - S_K$. Now, determine the area s_i (in number of detector pixels) of each subpixel for which the net luminance of that subpixel $K_i(x,y)$ is not less than a certain threshold fraction τ of the net maximum luminance: $K_i(x,y) \geq \tau(S_i - S_g - S_K)$ or $K_i(x,y) \geq \tau(S_i - S_d)$. We can

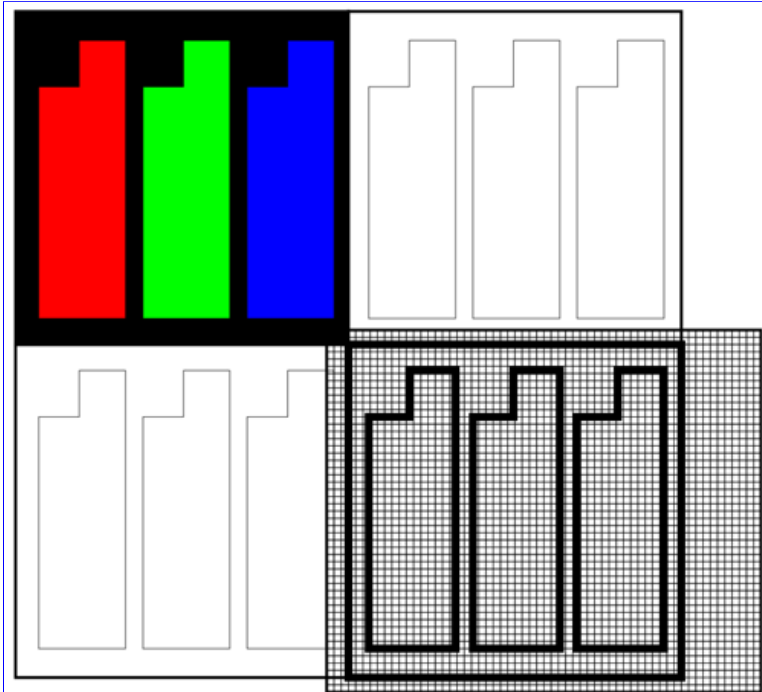


Fig. 1. A 60H x 50V array detector measuring a single RGB pixel.



rewrite this in terms of the measured quantities $S_i(x,y) \geq S_d + \tau(S_i - S_d) = \tau S_i + (1 - \tau)S_d$, which we probably could have written down directly. The threshold fraction τ used should be reported. We recommend either 5 % ($\tau = 0.05$) or 10 % ($\tau = 0.1$). The fill factor is then defined as $\frac{A_{\text{filled}}}{A_{\text{pixel}}}$, where A_{filled} is the area (in detector pixels) of all subpixels brighter than the threshold relative to each subpixel, and A_{pixel} is the area allocated to the entire pixel. (Some documents use a 50 % threshold. However, the eye perceives the size closer to the 5 % or 10 % threshold. In fact, a 50 % level to the eye is an L^* of 0.5 whereby $L^* = (L/L_W)^{(1/3)}$ gives a luminance for 50 % perception of $L = 0.125 L_W$. This underscores the reasonableness of the 5 % or 10 % value for the threshold.) Note that the veiling glare does not ultimately have to be measured explicitly since it is implicitly contained within S_d .

It is recommended that the magnification of the optical system be sufficiently high such that the smallest horizontal or vertical dimension of each subpixel can be resolved and quantized by at least 10 detector pixels (preferably more) assuming an array detector is used. Use a calibrated ruler such as a graticule scale for a measuring loupe or a microscope calibration ruler in order to determine the size associated with each array detection pixel should their areas need to be measured. Then simply count the number of array detection pixels that have a luminance greater than or equal to the threshold $S_d + \tau(S_i - S_d)$ for each display subpixel within a pixel.

Keep in mind that if an optical system is used such as a microscope or a system where the lens of the LMD subtends a significant angle (large θ_L), the uncertainty in the measurement increases. The lens subtense limit specified in this document is 2° and is difficult to maintain in producing high-magnification images unless a long-distance microscope is used. Tests may have to be done to assure that too wide a lens angular aperture will not perturb the measurements. Most will be faced with using a lens system that exceeds the 2° limit. If that is the case, a note of the optical arrangement should be made in the reporting document. In all cases report the fill factor and the threshold fraction employed.

REPORTING: Report the threshold (if used), the area of the display pixel, the area of the display subpixels above the threshold (if used), and the fill factor. Report the fill factor to no more than three significant figures. When reporting in percent, round off to the nearest integer percent.

COMMENTS: None.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting Example

Threshold	10 %
Pixel Area	6724 px
Filled Area	3792 px
Fill Factor	0.564
in percent	56 %

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis of Sample Data (Using an Array Detector)

Threshold τ	10 %	Luminance of black area, S_d (counts)	7296
Pixel coverage by detector pixels	82 x 82	Pixel area a in detector pixels (detector pixels)	6724
Subpixel	Maximum Luminance S_i , (in counts)	Threshold Level $\tau S_i + (1 - \tau)S_d$, (in counts)	Area Above Threshold (in detector pixels)
Red	21757	8742	1239
Green	27268	9293	1381
Blue	20774	8644	1172
Total area above threshold in detector pixels			3792
Fill factor			0.564



7.5 SHADOWING

ALIAS: cross talk, large area cross talk, cross coupling, streaking, trailing

DESCRIPTION: Measure the worst-case shadowing in eight-levels of gray. **Units:** Percent perturbation of the luminance of the gray shade. **Symbol:** None.

Shadowing refers to how one part of the screen can affect another part of the screen usually along rows or columns. Since the eye is a good edge detector, the slightest amount of shadowing usually is objectionable and may be found to be difficult to measure accurately. Shadowing is illustrated in Fig. 1 in the third screen from the top. What we measure here is worst case luminance shadowing of eight levels of gray. There can be similar effects with colors where the luminance may or may not be affected significantly. A color shift metric such as $\Delta u'v'$ or ΔE could be used.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

Note that all the patterns referred to in the setup below can be found in the files FPDMAILL. However, the levels of the gray boxes in the five positions and the background must be changed appropriately for the worst-case shadowing (to cover all possibilities would require 560 frames).

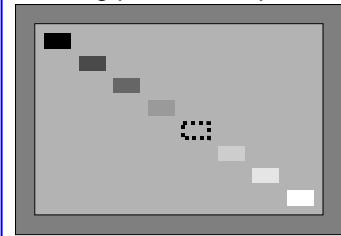
Establishment of Worst-Case Shadowing: Using a series of diagonal boxes of eight gray shades, change the background gray shade over all eight gray shades (other patterns are acceptable so long as all combination of the eight gray shades are examined for shadowing). Look for the worst-case of shadowing. It may be necessary to quickly measure the shadowing: If L_s is the perturbed luminance of the background and L_{bkg} is the background luminance without perturbation, then the shadowing measure is $|L_s - L_{bkg}|/L_{bkg}$. Once the worst case shadowing gray shades have been determined, G_{bkg} and G_s , proceed to the next part of setup.

Patterns for Shadowing Testing: There are a total of ten patterns used in this measurement: five single box patterns and five full-screen gray-level patterns interleaved. The sequence of five box patterns has a box sequentially placed (A) above, (B) to the left of, (D) to the right of, (E) below, and (C) at the center of the screen, one box for each pattern (this is the reading order in several languages: left-to-right, top-to-bottom). The edge boxes are centered along the closest side. The box sides are approximately 1/5 to 1/6 the width and height of the screen, and the box is separated from the edge of the screen by approximately half its width or height—see Fig. 1. Placement of the boxes should be $\pm 5\%$ of the linear dimensions of the screen. The command level of the boxes is G_s and the background command level is G_{bkg} . Each one-box pattern is separated in the sequence by a blank full screen of gray level G_{bkg} .

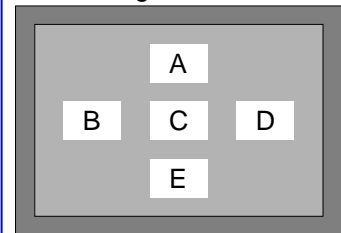
PROCEDURE: After having selected the worst-case shadowing during the initial setup, start with an edge box, for example, at the B position. Measure the luminance at center and at the position opposite to the box (position D). Go to the next pattern without the box and measure at positions C and at the center. Repeat this procedure for the other edge boxes (at A, D, and E). When the box is at the center position C, measure at each of the other box positions A, B, D, and E (not at center, obviously). The exact position of the area at which the measurement is made does not need to be precise, within $\pm 5\%$ of the linear dimensions of the screen will do. Determine the worst-case shadowing configuration (worst case being the greatest change in luminance with and without the box present). Select the worst-case shadowing box position from all the measurements made and secure the LMD in the position to repeat the measurement of the worst-case configuration. With the LMD in a secure position so it will not move relative to the screen, measure the luminance with the box present L_s and without the box present L_{bkg} . Critical alignment of the LMD is not necessary, but when the final measurement is made it is important that the LMD not move relative to the screen.

ANALYSIS: The shadowing S is expressed in percent: $S = 100\% |L_s - L_{bkg}|/L_{bkg}$.

Testing pattern sample:



Measuring areas:



Measurement example:

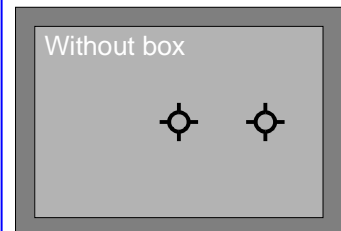
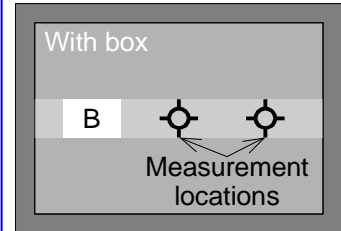


Fig. 1. Testing pattern, sample box positions, and measurement example with box at the C position.



REPORTING: Report (1) the maximum shadowing in percent, where the measurement was made, (2) the background gray shade in percent of white (white being 100 % and black, x %, whatever fraction black is of white) and/or level (7=white, 0=black), (3) the box gray shade (report in same format as the background), and (4) the position of the box used (A-D) to produce the shadowing. In the report sample below, B refers to luminance taken with the box present, and N refers to the luminance taken with no box present.

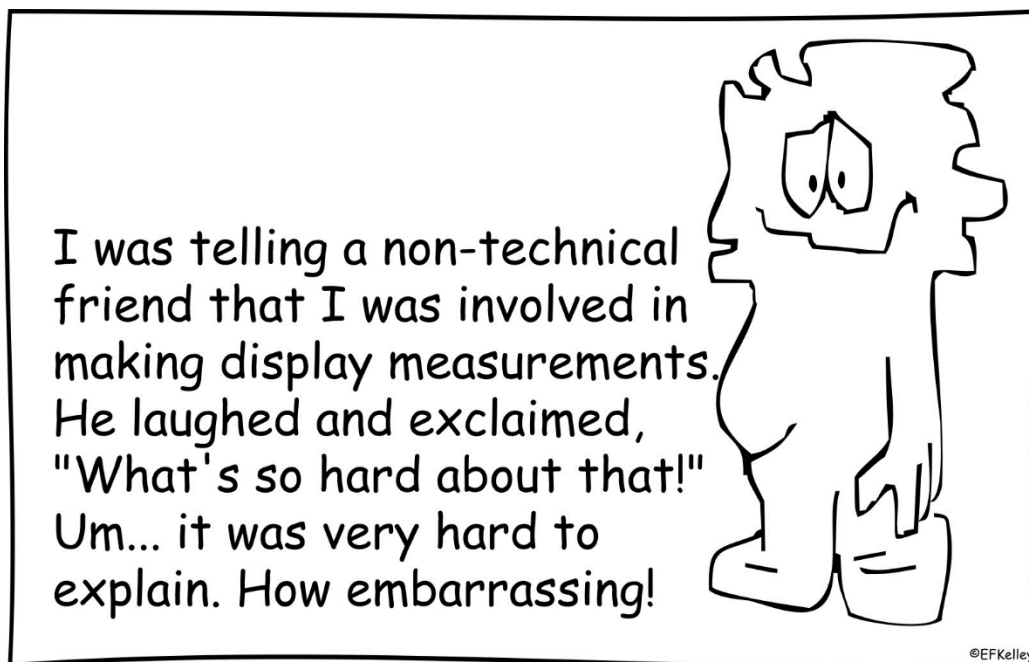
COMMENTS: Depending upon technology, there could be some dependencies on gray scale (addressed in this procedure) and color (not directly addressed herein). Sixteen gray levels can optionally be used if desired. The worst case is generally display dependent, in which case both the luminance level of the offending box and the background should be determined. Be careful of changing positions when taking the final luminance measurements because of the nonuniformities that may be inherent in the screen. If a stable mount cannot be provided, as when using a hand-held meter, consider using an alignment mask (an opaque card with holes at appropriate places through which the screen is measured).

The expression for the shadowing $S = 100\% |L_s - L_{bkg}| / L_{bkg}$ becomes infinite for zero luminance backgrounds ($L_{bkg} = 0$). This metric assumes that you will generally not be dealing with such a display.

Adaptation of the method to include colors is straightforward. After determining the two-color combination that produces the most offensive shadowing, follow the same procedure as above, but also measure the chromaticity coordinates (x, y). Instead of calculating a percent fractional change in luminance, compute a color change metric such as $\Delta u'v'$ for only color changes or ΔE to include the effects of luminance changes as well.

Different patterns may be employed as long as all interested parties agree to the modifications. For example, the boxes specified in this procedure may be too small to indicate shadowing that may be revealed by boxes that are larger than half of the screen height or width—or other shapes. For such extended boxes, it would no longer be possible to measure at the center of the screen. Again, any changes should be clearly documented.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting - Example		
Shadowing=100% B-N /N		
Box at (A-D)	C	L (cd/m ²)
Box (0-7)	0	B=box 95
Bkg. (0-7)	7	N=no box 103
Shadowing, S (%)		7.8 %





7.6 DEFECTIVE PIXELS

There are three parts of this analysis: (a) How we specify, categorize, and measure a defective pixel; (b) how we specify, categorize, and measure the clustering density; and (c) how we specify a minimum defective pixel separation (if such a specification is necessary). Since the clustering density—the number of defects per unit area or number of pixels—is a quantity that gets smaller as the quality of the screen improves, we define a metric that increases as the screen improves. The “clustering quality” or “defect dispersion quality” is defined as the number of good pixels per number of bad pixels. This clustering quality is large, generally several thousand, and increases with fewer defects. The clustering quality metric is also independent of screen size since it is based on the relative number of pixels rather than the area. All interested parties must mutually agree which specifications are employed to derive the defective pixel analysis. These are legacy metrics from the FPDM.

7.6.1 DEFECTIVE PIXEL CHARACTERIZATION & MEASUREMENT

DESCRIPTION: We discuss a method to characterize pixel defects.

Defective Pixels are pixels that operate improperly when addressed with video information. For example, a pixel addressed to turn black may remain white. If it never changes state, it is said to be a **stuck** pixel. If it changes state without the proper addressing signal, it may be **intermittent**. Detailed classification of defective pixel types follows below.

For another method of classification of pixel defects that characterizes a display, ISO 13406-2 [1] may be used at the user's discretion. The ISO classification defines the class of the display based upon the number of defects. We clarify pixel defect types further.

Note that defective column and rows are not truly pixel defects (e.g., driver-related problems, address-line problems, etc.), but may have the same characteristics as defined by defect types 1–5 in this section. It is up to the user to determine if any row and pixel defects are acceptable. They would be reported as **defective rows** or **defective columns**. Often people find that column and row defects are unacceptable.

Thresholds of observability: In what follows we discuss pixels that are stuck on and stuck off by saying their luminance is either always above a white threshold or below a black threshold. There are two types of thresholds: luminance thresholds and lightness thresholds. (1) **LINEAR LUMINANCE THRESHOLD:** Historically, the white threshold was 75 % of the full-white-screen luminance, and the black threshold was 25 %. The problem with this is that the luminance scale is a linear scale and does not relate well to what the eye sees as the white or black quality of the pixel. Thus, a 25 %-luminance-of-white added to black appears to the eye as a 57 % relative lightness. A much darker pixel than this would be quite visible against a dark background and could be objectionable. Also, the 75 %-luminance-of-white pixel appears to the eye as 89 % of white, and it may even be hard to identify well in a sea of white pixels. (2) **NONLINEAR LIGHTNESS THRESHOLDS:** To describe the dark and light thresholds as what the eye would see we need to use a lightness scale, and $L^* = (L/L_w)^{(1/3)}$ may be the best candidate at the present time—see § B9 Nonlinear Response of the Eye, and § B1 Radiometry, Photometry and Colorimetry Summary. If we specify lightness thresholds as what the eye would perceive to be 25 % and 75 % lightness between black and white, we would need the luminance threshold of black at 4.415 % and of white at 48.28 % of the white luminance. What is important is what the eye sees, so we would suggest that the lightness thresholds be adopted. However, the luminance thresholds have such an ingrained history, we felt that we had to include them here. Whichever threshold criterion is chosen (or any other criterion used), it should be negotiated by the interested parties and should be reported clearly.

SETUP: The visibility of pixel defects depends on both the type of defects and the video being displayed. For example, pixels that are stuck white will not be visible on an all-white display but will be obvious on a black screen. Therefore, the user must change the video content as appropriate to observe the defective pixels.

PROCEDURE: Defective pixels are usually assessed visually, as it is very difficult to properly measure them. A thorough analysis would be to measure each pixel and account for glare contributions to any dark pixel encountered. *Even if the defective pixels are identified by the eye and then measured to see if they fall within or without a threshold, veiling glare must be considered to obtain even an approximate measurement of a dark pixel in the presence of a white background—see A2.1,*

Thresholds of Observability			
Threshold Criterion	Required Luminance Thresholds, L_{WT}, L_{BT}	Lightness Perceived by Eye, L^*	Partial Pixel Areas† S_{UT}, S_{LT}
25 % Luminance (L)	25 %: $L_{BT} = 0.25L_w$	57.1 %	25 %: $S_{LT} = 0.25S_p$
75 % Luminance (L)	75 %: $L_{WT} = 0.75L_w$	89.4 %	75 %: $S_{UT} = 0.75S_p$
25 % Lightness (L^*)	4.415 %: $L_{BT} = 0.04415L_w$	25 %	4.415 %: $S_{LT} = 0.04415S_p$
75 % Lightness (L^*)	48.28 %: $L_{WT} = 0.4828L_w$	75 %	48.28 %: $S_{UT} = 0.4828S_p$

† S_p is the total area of the light-producing part of the pixel, e.g., the total subpixel area.



Veiling Glare and Lens Flare Errors. Conditions for viewing pixel defects are subject to supplier/customer agreements. Guidelines may be considered as follows: Dark room conditions are recommended for the best viewing of pixel defects. The observer may look at any distance or angle to both observe the defects and assess them and may use a magnifying device to better categorize them by type. Again, any video pattern may be used to help observe defects. In the following material, S is a measure of areas associated with the pixel.

ANALYSIS: In any final reported result, all fractional pixels are rounded up to a whole number. Five types or classifications define defective pixels. Type 1, 2, and 3 are luminance-related, type 4 is spatially related, and type 5 is temporally related. There is a white threshold level L_{WT} , a black threshold level L_{BT} , a partial-pixel-area upper threshold S_{UT} , and a partial-pixel-area lower threshold S_{LT} , upon which these classifications are based:

- 1) **On Pixels (Stuck On):** Luminance always above the white threshold independent of video content, $L > L_{WT}$. Can be observed using a black screen. These pixels appear as bright pixels on a black background.
- 2) **Dim Pixels (Stuck Dim):** Luminance is always between the white threshold and the black threshold independent of video content, $L_{BT} < L < L_{WT}$. They can be observed using a white and then a black screen. These pixels appear as a gray pixel independent of a white or black background.
- 3) **Off Pixels (Stuck Off):** Luminance is always below the black threshold, $L < L_{BT}$. They can be observed using a white screen. These pixels appear as dark pixels on a white screen.
- 4) **Partial Pixels:** Pixels that have defective subpixels or area defects within a pixel, e.g., part of the pixel is stuck on or off. If S_p is the light producing area of a normal pixel, e.g., the combined area of the subpixels, then there are three active-area regimes in which the pixel can operate: (1) The active area S of the pixel is less than the lower threshold $S < S_{LT}$, in which case the pixel is mostly inoperative and stuck either on or off. (2) The active area of the pixel is greater than the upper threshold $S > S_{UT}$, in which case the pixel is mostly operational and not to be considered a defective pixel. (3) The case of the partial pixel where the active area of the pixel is between the threshold limits $S_{LT} < S < S_{UT}$.
- 5) **Temporal Pixels:** Pixels that exhibit temporal variations not related to any steady-state video input. Temporal pixel defects may be intermittent, exhibit a sudden change of state, or be flickering. They can be observed using a white and/or a black screen.

(Note: For equating pixel defect types to those defined by ISO 13406 [1], the ISO type 3 can be considered to be the combination of the type 3, 4, and 5 defined in this document.)

A complete pixel defect specification would include setting limits for each type of defect n_i . The total number of defects is given by the sum

$$n_T = \sum_{i=1}^5 n_i \quad (1)$$

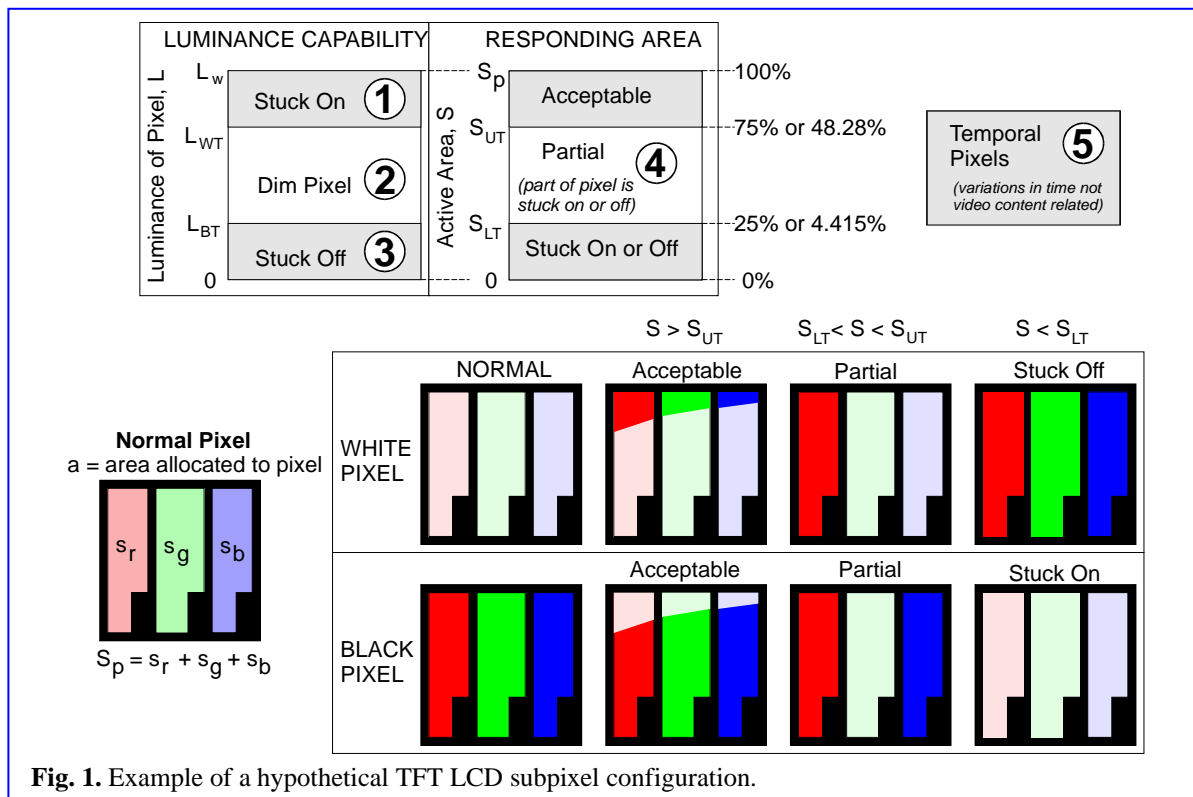


Fig. 1. Example of a hypothetical TFT LCD subpixel configuration.



These defects are not likely to evenly distribute themselves about the screen. There may be some bunching. This leads to the idea of clustering specifications as well as defect counts.

Defect Analysis Reporting Template						
Criteria	Lower Thresholds (%)	L_{BT}, S_{LT}	Upper Thresholds (%)	L_{WT}, S_{UT}		Clustering Quality
Type	1	2	3	4	5	Defect Dispersion Quality
Name	Stuck On	Dim	Stuck Off	Partial	Temporal	
Number Allowed	n_1	n_2	n_3	n_4	n_5	Q
Patterns:	(Describe screens used and any special method.)					

7.6.2 CLUSTERING CHARACTERIZATION & MEASUREMENT

Clustering of Defects: Clustering of defects is a way of characterizing the proximity or grouping of pixel defects. If a certain display has n defective pixels, then the proximity of the pixels can affect how objectionable the defects are and the usability of the display. For example, 20 pixel defects scattered randomly on a 1024×768 display will not be nearly as objectionable as they would be if they were clustered or contained within a confined area, such as within 10 % of the area of the display. If a total of n_T defective pixels were distributed absolutely uniformly about the surface of the display, then the minimum defect density would be n_T/N_T . Note that the area of the display is not in the denominator, but the total number of pixels for the display. This density is a density of defective pixels compared to the total number of pixels $N_T = N_H N_V$; therefore, this density is independent of display size. For example, if we allow $n_T = 20$ px and we have a 1024×768 screen, then the density would be $2.57 \times 10^{-4} = 1/3891$ defective pixels per screen pixels. However, given that we have n_T defective pixels, n_T/N_T is the absolute lowest pixel density that may be obtained. Clearly that will not be the case in general. Therefore, we will expect that the clustering density specification will allow a higher pixel density than this minimum, probably significantly higher. Densities are not always very intuitive, so we introduce a **defect dispersion quality** metric as the inverse of the density:

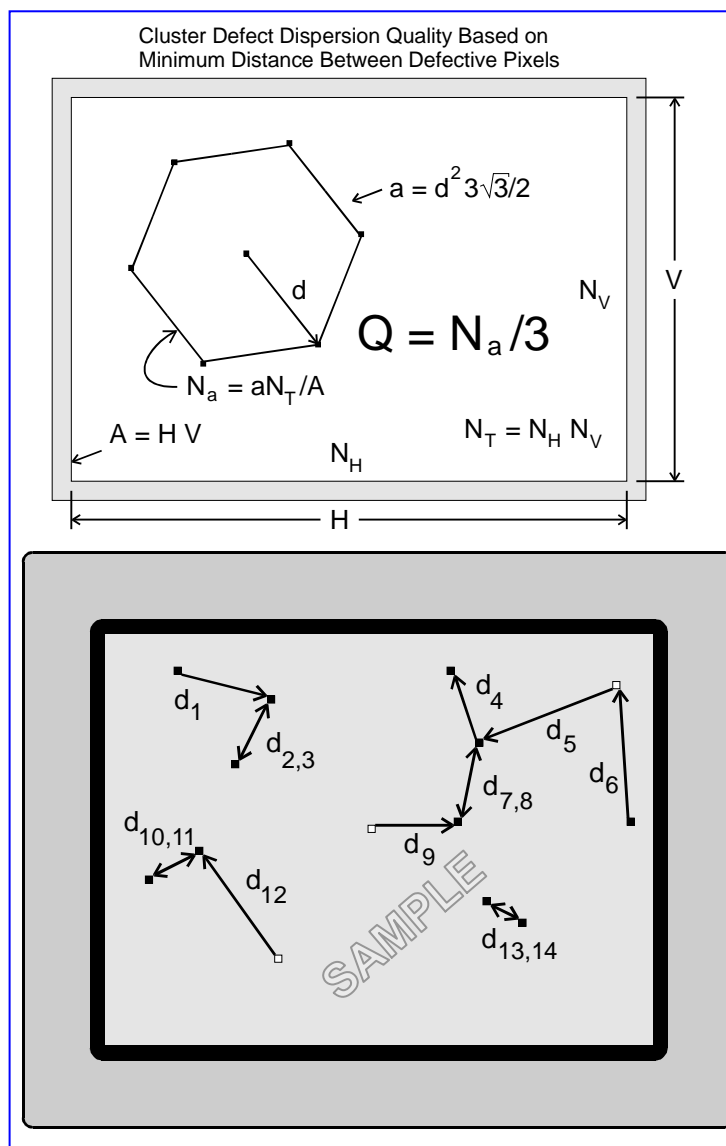
Defect dispersion quality or Clustering

Quality:

Q = the number of acceptable pixels for each defective cluster pixel. Often we will use “**clustering quality**” as a short name for Q . The clustering quality is the inverse of the clustering density. Given N_T as the total number of pixels in the display and n_T as the total number of defects, the maximum that the clustering quality can be is

$$Q_{\max} = N_T/n_T. \quad (2)$$

This is equivalent to requiring that the defects be absolutely uniformly spread over the surface of the screen—a situation that would be rarely obtained in practice.





Consider two defective pixels separated by a distance d . We want to develop an expression for the largest defect density based on that distance. The highest density is obtained by centering a hexagon on one pixel and imagining other pixels at the remaining vertices of the hexagon—all the pixels will be a distance d from each other, and the pattern can be repeated for the entire screen. How many pixels are there within the area of the hexagon? Image that the pixels were round and centered exactly at the vertices. One third of each vertex pixel lies within the hexagon. Thus, with six vertex pixels, one-third pixel each, plus the center pixel, we have the equivalent of three pixels per hexagon as worst-case packing. Obviously, this is an idealized case, but for large number of pixels, it should be adequate. The area of a hexagon with sides d is

$a = 3d^2 \sqrt{3}/2$, and the number of pixels within a is $N_a = aN_T / A$. The clustering density is $3/N_a$, and the clustering quality is then $Q = N_a/3$. Of course, pixels don't cluster in such a regular pattern. We can assume that they will randomly be distributed about the screen. We need to extend this to make it meaningful for randomly distributed pixels.

Consider a screen with defective pixels distributed randomly. We will assume square pixels. Each defective pixel $i = 1, 2, \dots, n_T$, will have a nearest neighbor a center-to-center distance d_i away. We define d to be the average nearest-neighbor distance between defective pixels or the mean minimum distance between defective pixels,

$$d = \frac{1}{n_T} \sum_{i=1}^{n_T} (d_i - P), \quad (3)$$

where we subtract the pixel pitch from each center-to-center distance d_i so that d goes to zero for all defective pixels touching each other in a row or column. In general, the P term will be of little consequence for many screens.

To determine the mean minimum distance between defective pixels, proceed as follows:

1. List the (x, y) position of all defective pixels in either a distance (e.g., in mm) or pixel coordinates.
2. For each defective pixel in the list, compute the minimum center-to-center distance to any other pixel in that list. Often a pair of nearby defects will each have the same minimum distance to each other.
3. Compute the mean of the minimum center-to-center distances. If you use pixel coordinates instead of pixel distances, convert the pixel coordinates to a distance by multiplying the mean result by the pixel pitch P .

$$d_i \text{ measured in units of distance: } d = \frac{1}{n_T} \sum_{i=1}^{n_T} (d_i - P), \quad (4)$$

$$d_i \text{ measured in units of pixel coordinates: } d = \frac{P}{n_T} \sum_{i=1}^{n_T} (d_i - 1). \quad (5)$$

NOTE: If you are attempting to determine that a candidate DUT meets its specified clustering criterion Q , first locate the closest two defective pixels and determine their separation d' ; if the clustering quality factor Q' based on this distance d' ,

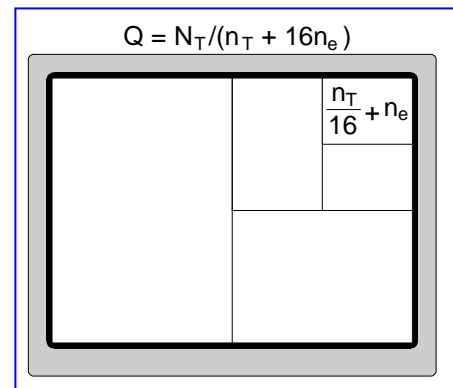
$Q' = d'^2 N_T \sqrt{3} / (2A)$ is greater than or equal to the specification requirement, $Q' \geq Q$, then it is not necessary to measure the distances between the rest of the defective pixels. The display definitely meets or exceeds the specified clustering quality. Alternatively, you can cut a circular hole in a piece of paper having a diameter of

$$d = \sqrt{(2QA) / (N_T \sqrt{3})}, \quad (6)$$

and search to see any two defective pixels can be found to fall within the circle. If not, then the display definitely meets or exceeds the clustering quality criterion. If using either of these tests, two pixels are found to be closer than d it does *not* mean that the display does not meet the clustering criterion. It simply means that a more thorough analysis will be required to determine the clustering quality, as described above.

With this definition, the clustering can be defined by the average distance between defective pixels d or by the clustering quality Q . Assuming square pixels, there are two more ways to express clustering: the smallest fraction of the horizontal screen size permitted between defective pixels $f = d/H$, and the minimum number of horizontal pixels $n_d = d/P$ permitted between defective pixels (P is the pixel pitch for square pixels). If square pixels are not used, the formulation will work well replacing P with $P' = \sqrt{P_H^2 + P_V^2}$, provided d is confined to being always positive (in the event that all pixels touch or nearly touch—again, we can hardly expect this to be a routine problem).

PROCEDURE: There are two cases, you are trying to measure the clustering quality of a display, or you are trying to specify the clustering quality of a display.





Measurement of Clustering Quality: Follow the three steps leading to Eqs. 4 and 5 to obtain the mean minimum distance between defective pixels d . The clustering quality is then

$$Q = \frac{d^2 N_T \sqrt{3}}{2A}, \quad (7)$$

where N_T is the total number of pixels making up the display and A is the area of the display. See the table for other means of determination d and Q when d is measured in the fraction of screen width or the number of pixels between defects.

Determination of Requisite Clustering Quality: An excellent way to estimate how many defects are tolerable is to subdivide the screen into boxes taking half of each box until you reach 1/16 the area. How many defective pixels will you tolerate in the small box? If you have already specified the total number of defects allowed n_T , then there can be $n_T/16$ pixels plus some excess pixels n_e . You must select what n_e must be. The clustering quality is then $Q = N_T/(n_T + 16n_e)$. If you don't know what value for n_T is reasonable for your task, then you can specify how many defective pixels n you will tolerate in the 1/16 box, and then the clustering quality can be defined as $Q = N_T/(16n)$.

Discussion: Here you have some idea of how many defective pixels you will tolerate, that is, you know n_i ($i = 1, 2, \dots, 5$) and n_T , or you know how many pixels you will tolerate in a 1/16 box. You probably will never dare require an absolute uniform distribution of defects using $Q_{\max} = N_T/n_T = 39322$, so what we need is a way to estimate a reasonable value of Q . It may be tempting to select a distance d and then calculate $Q = d^2 N_T \sqrt{3}/2A$. This can be done but it will probably not yield what you want. Consider an example. Suppose we desire a 1024×768 pixel screen having a horizontal size of 245 mm and vertical size of 184 mm, and we want $d = 20$ mm to be the mean minimum distance between defects. This gives $Q = 6043$, and for the entire area A at that density of defects, we could have 130 defective pixels. So, let's say you limit the total number of defects to $n_T = 20$ and you think you've taken care of the problem. Not so, for all the pixels could be clustered in one region of the screen all with a distance d between them, and that is probably not what you want either. Now use the 1/16 box: if the defects were evenly distributed, we'd find $n_T/16 = 1.25$ pixels per 1/16 box. If you will allow one more pixel $n_e = 1$, then $Q = 21845$; if $n_e = 2$, then $Q = 15124$. This in itself may not adequately solve the problem of specification, for even under the condition of using the 1/16 box criterion, you can still have two pixels touching and meet the cluster quality criterion established by the 1/16 box criterion. This is why we introduce the minimum defect separation below in § 7.6.3.

Extension to More Complicated Clustering Quality Factors: Clearly, should it be necessary and if a more detailed clustering description is required, a clustering quality could be defined for each type of pixel defect. Another way to deal with the different types of pixel defects if they are not considered equally objectionable, is to use a weighting factor w_i in

the expression of the mean minimum distance between defective pixels: $d = \frac{1}{n_T} \sum_{i=1}^{n_T} w_i w_j (d_i - P)$, where w_i is the weighting

factor for the i^{th} pixel and w_j is the weighting factor for the its nearest neighbor, the j^{th} defective pixel. For example, the weights might be 1 for a stuck-on or stuck-off pixel, 1/2 for a dim pixel, 1/3 for a partial pixel, and 1 for a temporal pixel.



7.6.3 MINIMUM DEFECT SEPARATION — d_{\min}

If two defective pixels are very close together and all other defective pixels are widely separated, the clustering quality may be met and the number of defective pixel types may also be met, but the fact that the two defective pixels are so close together may be objectionable. Thus, the minimum allowable distance between defective pixels d_{\min} may also be specified if it is necessary to do so. Again, this minimum distance can be specified in terms of the distance on the screen, the number of pixels in the separation, or the fractional width of the horizontal screen.

Table 1. Relationships Regarding Clustering Quality Q

Based on d (the mean nearest-neighbor distance or mean minimum distance between defective pixels)		
$Q = \frac{N_a}{3}$	Clustering quality	Number of acceptable pixels for three ideal defective pixels distributed uniformly—this is the basis of the model.
$Q = \frac{aN_T}{3A}$	Clustering quality	Clustering quality in terms of the area a of a hexagon, the total number of pixels, and the area of the screen.
$a = \frac{d^2 3\sqrt{3}}{2}$	Area of hexagon with side d .	
$Q = \frac{d^2 N_T \sqrt{3}}{2A}$	Clustering quality	Clustering quality expressed in terms of the mean minimum distance between defective pixels. Measure d, calculate Q.
$d = \sqrt{\frac{2QA}{N_T \sqrt{3}}}$	Mean minimum distance between defective pixels	Should you know Q and you want to determine the mean minimum distance d upon which the determination was made. Given Q, determine d.
$d = \frac{1}{n_T} \sum_{i=1}^{n_T} (d_i - P)$	d measured in units of distance	
$d = \frac{P}{n_T} \sum_{i=1}^{n_T} (d_i - 1)$	d measured in pixel coordinates	
Based on f (the mean nearest-neighbor distance in terms of the fractional distance of the screen)		
$f = d / H$, or $d = fH$	Characterizing d by a fraction of the horizontal screen	
$Q = \frac{f^2 \alpha N_T \sqrt{3}}{2}$, derivation: $Q = \frac{d^2 N_T \sqrt{3}}{2A} = \frac{f^2 H^2 N_T \sqrt{3}}{2HV} = \frac{f^2 \alpha N_T \sqrt{3}}{2}$		
Based on n_d (the mean nearest-neighbor distance in terms of a number of pixels on the screen)		
$n_d = d/P$, or $d = n_d P$	Characterizing d by a number of pixels	
$Q = \frac{n_d^2 \sqrt{3}}{2}$, derivation: $Q = \frac{d^2 N_T \sqrt{3}}{2A} = \frac{n_d^2 P^2 N_T \sqrt{3}}{2HV} = \frac{n_d^2 \sqrt{3}}{2}$		
Definitions used in the above:		
$N_a = aN_T/A$	Number of pixels in an area a	
$A = HV$	Area of the screen (the active, viewable, image-producing area)	
$N_T = N_H N_V$	Number of pixels on screen in terms of number of horizontal and vertical pixels	
$H = N_H P_H$ $H = N_H P$ (square pixels)	Number of horizontal pixels in terms of the horizontal pixel pitch	
$H = N_V P_V$ $H = N_V P$ (square pixels)	Number of vertical pixels in terms of the vertical pixel pitch	

REFERENCE:

- [1] ISO 9241-303 (2011). *Ergonomics of human-system interaction — Part 303: Requirements for electronic visual displays*. Geneva: International Organization for Standardization. <https://www.iso.org/standard/57992.html>.



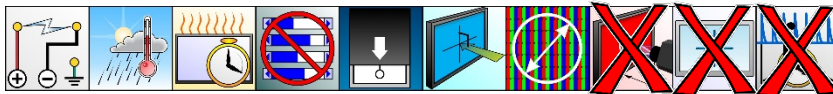
7.7 EFFECTIVE RESOLUTION

ALIAS: sharpness

DESCRIPTION: Measure the luminance of vertical or horizontal step patterns on the display with a slightly tilted array LMD. Calculate the spatial frequency response (SFR) of the image by a slanted-edge algorithm. Obtain resolution at a specified drop (e.g., 50%) of SFR of the DUT. **Unit:** 1/pixel. **Symbol:** $f(50\%)$.

APPLICATION: All displays that emit light.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Generate a step edge pattern on the DUT. The digital inputs of the step-edge pattern can be freely defined for further studies. The LMD must be array-type, and is placed with a tilt angle about 5° relative to the step edge. The LMD can be a commercial one or a digital camera with its output calibrated to proportional to luminance. The ISO 17321-1 standard is recommended for the calibration procedures [1]. The spatial frequency response (SFR) of the LMD ($M_C(f)$) should be better than the combined SFR of LMD and display ($M_T(f)$). $M_C(f)$ can be measured according to the ISO 12233 standard [2]. The number of pixels of LMD that cover one pixel of display is recommended more than two.

PROCEDURE:

1. Capture the image, and convert the output data to luminance.
2. Calculate total spatial frequency response (SFR) $M_T(f)$ in the region of interest (ROI) by the slanted-edge method, which can be found in the following section, § 0.
3. Calculate the global Michelson contrast C_M .
4. Compute SFR of display [$M_D(f)$] from C_M , $M_T(f)$, $M_C(f)$. Obtain resolution from the SFR curve.

ANALYSIS: The SFR of displays can be written as

$$M_D(f) = C_M M_T(f) / M_C(f) \quad (1)$$

If $M_C(f)$ is much wider than $M_T(f)$, $M_D(f)$ can be approximated with $C_M M_T(f)$. The resolution $f(n\%)$ is obtained by finding the spatial frequency at a specified drop of $n\%$ in $M_D(f)$ curve.

REPORTING: Report the resolution to no more than three significant figures using the value obtained in the previous sections. The test conditions such as C_M , and average luminance L_A should also be reported.

PLEASE NOTE: This method is being researched and revamped for clarity. It is not recommended to be used at this time.

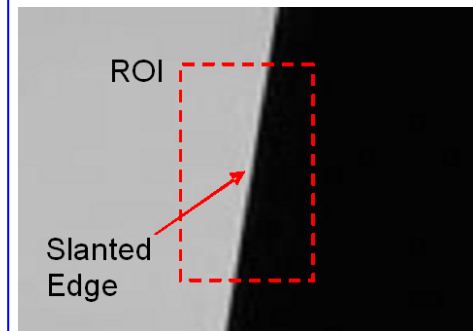
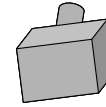
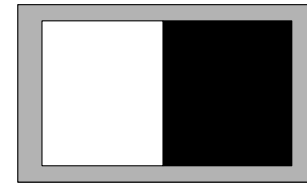


Fig. 1. Tilted array detector observing a step pattern. ROI is region of interest.

—SAMPLE DATA ONLY—

Do not use any values shown in this section to represent expected results of your measurements.

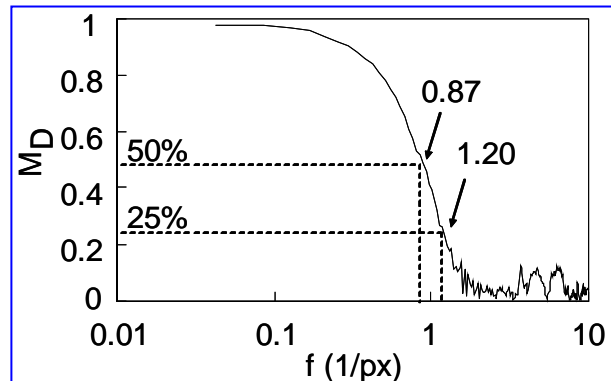


Fig. 2. Spatial frequency response example curve.



COMMENTS: The resolution greater than 1 is reasonable because most modern displays (e.g., LCD) are constructed with sub-pixels, and sometimes digital sharpening on the display is performed. SFR can also be combined with contrast-sensitivity function (CSF) to obtain the perceptual resolution.

REFERENCES:

- [1] ISO 17321-1, "Graphic Technology and Photography - Color characterization of digital still cameras (DSCs) using color targets and spectral illumination", First edition, International Organization for Standardization (1999).
- [2] ISO 12233, "Photography - Electronic still-picture cameras - Resolution measurements", First edition, International Organization for Standardization (2000).

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

Horizontal		Vertical	
L_A	187	L_A	189
C_M	0.98	C_M	0.97
$f(50\%)$	0.87	$f(50\%)$	0.86

7.7.1 SPATIAL FREQUENCY RESPONSE DETERMINATION

DESCRIPTION: Spatial frequency response (SFR, or MTF) is the basis for studying sharpness, DMTF, etc. of displays. The calculation method of SFR in this appendix was modified from on the standard slanted edge method [1], which is an improvement of knife-edge method to increase accuracy of calculation of SFR.

PROCEDURE:

Examples in Fig. 1 corresponding to the subsequent steps for the determination of SFR are shown in following.

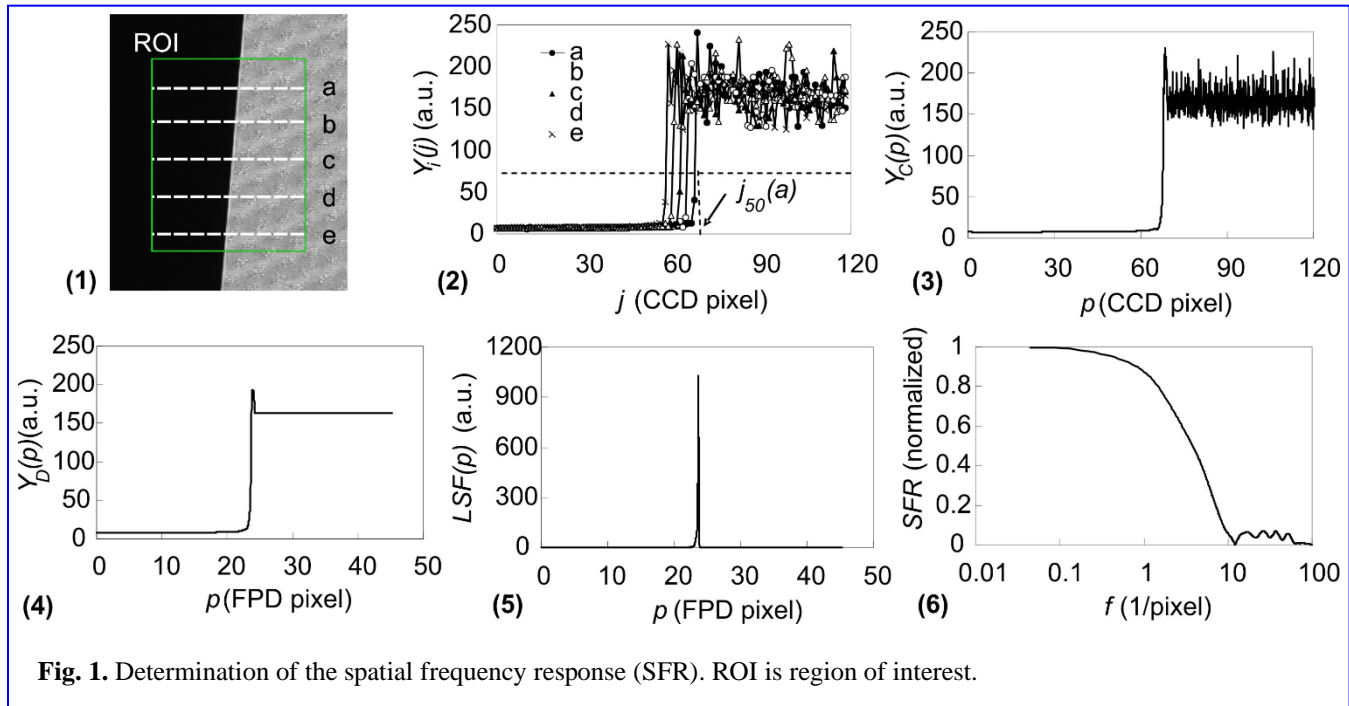


Fig. 1. Determination of the spatial frequency response (SFR). ROI is region of interest.

1. Select **region of interest (ROI)** from the image, and convert unit of output to luminance proportional.
 - 1.1 Select a ROI including slanted edge by a rectangle ROI tool. The minimum size of ROI is suggested more than 50x50 pixels.
 - 1.2 If a digital still camera (DSC) is used, convert the unit of output proportional to luminance (Y). The RGB outputs from a color DSC should be first gamma-converted, and then linearly combined to Y.

$$Y = a_1 f_1(R) + a_2 f_2(G) + a_3 f_3(B) \quad (1)$$

where the constants a_1 , a_2 , a_3 and the gamma functions f_1 , f_2 , f_3 can be found by a standard procedure [2].

2. Obtain Y-distribution with column j of each row i [$Y_i(j)$] in the ROI. $Y_i(j)$ of the rows a , b , c , d , e in the example figure can be easily gotten by extracting luminance value along the rows.
3. Shift $Y_i(j)$ with amount of δ_i to $Y_i(j-\delta_i)$. Merge all $Y_i(j-\delta_i)$ to a single function $Y_c(p)$.
 - 3.1 δ_i is generally non-integer and is calculated with the equation



$$\delta_i = m \cdot i + c \quad (2)$$

where the slope m and intercept c are determined by best fit of locations $j_{50}(i)$ of about 50% transition of each $Y_j(j)$.

3.2 $Y_C(p)$ is densely spaced with non-integer CCD pixel p .

4. Remove aliasing and noise from $Y_C(p)$ to get $Y_D(p)$ by the improved wavelet denoise method in the following section, § 7.7.2. Convert unit of p from CCD pixel to FPD pixel. The converting ratio can be calculated by counting the CCD pixels of a line with known FPD pixels.

5. Compute line spread function $[LSF(p)]$ by numerical differentiation on $Y_D(p)$.

5.1 For further processing, resample $Y_D(p)$ to equal spaced function $Y'_D(p)$ with spacing δp .

5.2 An example numerical differentiation is written as

$$LSF(p) = [Y'_D(p) - Y'_D(p - \delta p)] / \delta p \quad (3)$$

6. Fourier transform on $LSF(p)$ to get SFR .

6.1 Typical Fourier transformation is written as

$$F_k[LSF(p)] = \sum_{n=0}^{N-1} LSF(n \cdot \delta p) e^{-j2\pi kn/N} \quad (4)$$

where N is the number of sampling points of $LSF(p)$. There are many commercial or shared libraries for performing Fourier transformation (especially FFT).

6.2 Take modulus of the Fourier transformed data, and get the normalized SFR by the equation

$$SFR_k = |F_k[LSF(p)] / F_0[LSF(p)]| \quad (5)$$

where $F_0[LSF(p)]$ is the dc component.

REFERENCES:

- [1] ISO 12233, "Photography - Electronic still-picture cameras - Resolution measurements", First edition, International Organization for Standardization (2000).
- [2] ISO 17321-1, "Graphic Technology and Photography - Colour characterisation of digital still cameras (DSCs) using colour targets and spectral illumination", First edition, International Organization for Standardization (1999).

7.7.2 IMPROVED WAVELET DENOISE METHOD

DESCRIPTION: This is a method to separate modulation, aliasing, and noise from a response curve. For example, the gray-to-gray temporal response curve of a display can be processed by this method with less distortion.

PROCEDURE:

1. A measured curve $A_0(t)$ with parasitic modulation and noise is shown in the following example figure. It is first denoised to the curve $B_1(t)$, which still has un-removed modulation.

$$B_1(t) = D[A_0(t)] \quad (1)$$

where the notation $D[f(t)]$ means performing a wavelet-denoise processing on a curve $f(t)$.

2. To further remove the modulation, a white noise $n_1(t)$ is added to the $B_1(t)$ curve to get a $A_1(t)$ curve. $A_1(t)$ is again processed by the wavelet-denoise method to obtain the $B_2(t)$ curve.

$$A_1(t) = B_1(t) + n_1(t) \quad (2)$$

$$B_2(t) = D[A_1(t)] \quad (3)$$

The standard deviation of $n_1(t)$ is recommended less than one percent of the amplitude of $A_0(t)$.



- Repeat step 2 until the modulation is almost completely removed.

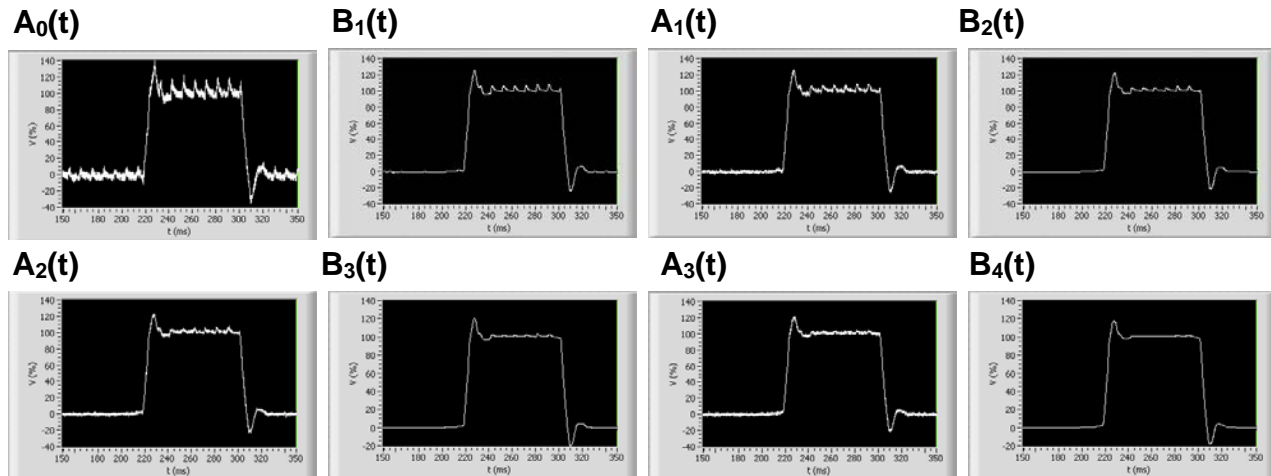


Fig. 1. Illustration of denoise method (vertical axes are in percent, horizontal axes are time in ms).

$$A_i(t) = B_i(t) + n_i(t) \quad (4)$$

$$B_{i+1}(t) = D[A_i(t)] \quad (5)$$

- The $B_4(t)$ curve in the above example is the final demodulated curve of $A_0(t)$.
- The example measured curve, modulation and noise, and processed curve is shown in Fig. 2:

- The theory of wavelet-denoise method would be found in many literatures and websites [1], and also explained in appendix Tech. Dis. S-3 of reference [1]. The wavelet-denoise tool can be developed with software packages such as C++ shared library, MATLAB® toolbox, LabVIEW® function library, and so on. The Haar wavelet with soft threshold setting and level setting no less than 10 is recommended for the purpose. Example of setting of a Labview® wavelet-denoise library is shown in Fig. 3:

[1] D. L. Donoho, IEEE Trans. Inform. Theory Vol. 41, p. 613 (1995).

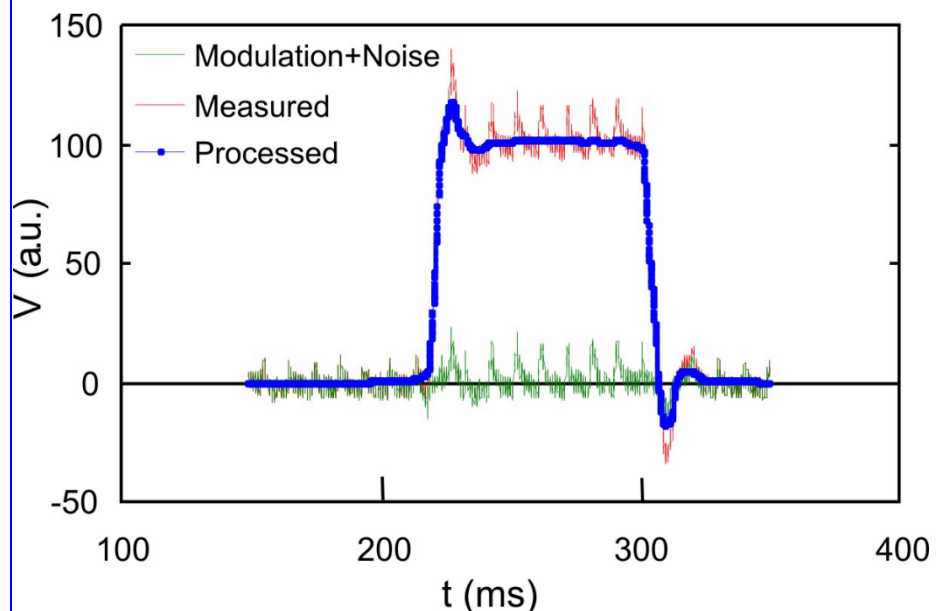


Fig. 2. Example of measured curve, modulation, noise and processed curve.

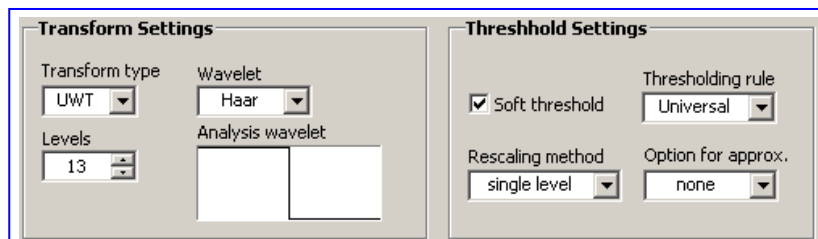


Fig. 3. Haar wavelet with soft threshold setting and level setting ≥ 10 .



7.8 RESOLUTION FROM CONTRAST MODULATION

ALIAS: effective resolution (see the previous section)

DESCRIPTION: We measure the resolution capabilities of a display compared to its advertised resolution or native resolution based on a threshold contrast modulation (Michelson contrast) associated with grille patterns.

Resolution refers to how well input signal pixels can appear separate and distinct to the eye when exhibited on the display. The number of alternate black and white lines that can be displayed with a stated minimum contrast modulation (Michelson contrast), the threshold contrast modulation C_T , indicates the resolution capability of the display. If the display fails to meet this criterion for a specified grille pattern created at the advertised (native) resolution of the display, then the actual resolution can be lower than the advertised (native) resolution. Here, the contrast modulation is defined as:

$$C_M = \frac{L_W - L_K}{L_W + L_K} \quad (1)$$

where L_W is the luminance of white grille lines and L_K is the luminance of black grille lines. We examine the values for horizontal and vertical resolution separately.

A higher contrast modulation threshold for text/graphics than for images can mean that the claimed resolution may be lower for text/graphics in some cases. Two thresholds are suggested below as guidance depending upon the task. Other thresholds may be used, if necessary, provided all interested parties are in agreement. Different tasks may require different thresholds to be used. The following thresholds are historical from the days of the CRT.

Text resolution (and graphics) require crisp edge definition and clear whites and blacks. We define the resolution for this use as the maximum number of alternating black and white lines that can be displayed with a threshold contrast modulation C_T of 50 % or more.

Image resolution typically does not require sharp changes in luminance. For monitors displaying images rather than text and/or graphics, we define the resolution using a minimum C_T of only 25 %.

SETUP & PROCEDURE: None. Measurements of $N \times N$ grille contrast modulations are specified in § 7.2.

ANALYSIS:

Calculate the resolution in number of resolvable pixels. Let N be the native resolution or advertised resolution of a display (either horizontal N_H or vertical N_V). If the contrast modulation of a 1×1 grille is less than one, then a more realistic resolution N_r is given by:

$$N_r = \frac{N}{n_r} \quad (2)$$

where n_r is the calculated grille line width in pixels for which the value of C_M is estimated by linear interpolation to be equal to the contrast modulation threshold C_T , for example, 25 % as depicted in Fig. 1. $C_M(n)$ specifies the contrast modulation from an $n \times n$ grille.

If $C_M(1) > C_T$ (e.g., 25 %), then $n_r = 1$ and the resolution is equal to the native resolution. For $C_M(1) < C_T$, use linear interpolation to calculate the value of n_r from the measured C_M values nearest to the threshold C_T (e.g., 25 %). In general, use values of C_M such that $C_M(n) < C_T < C_M(n+1)$, measured for grille patterns of n -pixels wide lines and $(n+1)$ -pixels wide lines.

$$n_r = n + \frac{C_T - C_M(n)}{C_M(n+1) - C_M(n)}, \quad \text{for } C_M(n) < C_T < C_M(n+1)$$

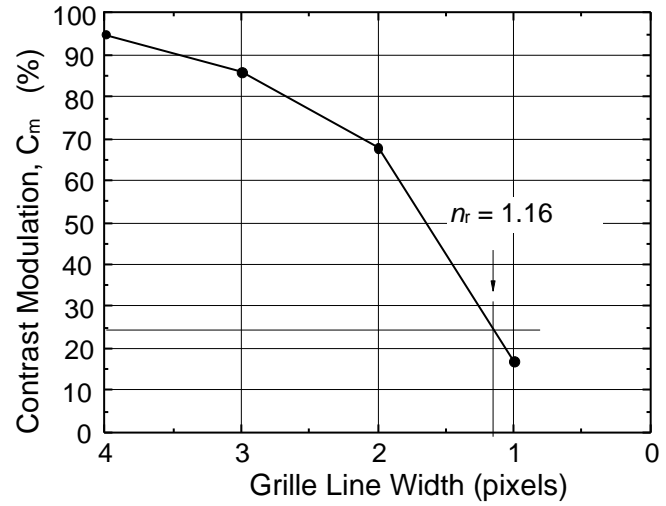


Fig. 1. Use linear interpolation to determine the value of n_r from contrast modulation measurements. An example of $n_r = 1.16$ is shown.



Example: Let $C_T = 25\%$, $C_M = 17\%$ for 1-pixel grille patterns, and $C_M = 68\%$ for 2-pixel grille patterns. Interpolate between these two data points to calculate the value of n_r for 25 % modulation, that is, using $C_T = 25\%$: for $n = 1$, $C_m(1) = 0.17$; $C_m(2) = 0.68$. For these values, n_r and the resolution are found to be

$$n_r = n + \frac{C_T - C_M(n)}{C_M(n+1) - C_M(n)} = 1 + \frac{0.25 - 0.17}{0.68 - 0.17} = 1.1568$$

$$N_r = \frac{N}{n_r} = \frac{1024}{1.1568} = 885 \text{ lines.}$$

Apply this criterion to the measured contrast modulation data C_M to assess the resolution capabilities of the display in units of pixels in both horizontal and vertical directions.

NOTE: The result of this evaluation is of practical importance when the line-pitch of the display can be continuously adjusted as it used to be the case with CRTs, and if the luminance modulation varies in a linear way with the pitch. Pixelated displays like LCDs, PDPs and OLED displays can generally only display grille patterns with fixed pitches as determined by the display pixel matrix layout. These pixelated displays can render grille patterns with 1x1, 2x2, 3x3, ... pixel widths, but non-integer ratios may not be able to be displayed on such pixelated displays.

REPORTING: Report the integer number of resolvable pixels using the values of C_M obtained in previous sections. Report as a pair of numbers for horizontal and vertical directions, $C_{MH} \times C_{MV}$, for each measurement location on the screen required.

Worst location is defined as the test location on the screen where the minimum combined horizontal and vertical contrast modulation occurs. The combined contrast modulation is the magnitude calculated using the root-mean-of-squares:

$$C_M = \sqrt{(C_{MH}^2 + C_{MV}^2)/2},$$

where C_{MH} is horizontal contrast modulation and C_{MV} is vertical contrast modulation of white lines.

COMMENTS: Resolution is often the first specification one asks about a display. It is essential to distinguish between the concepts of *addressability* and *resolution*:

1. **Loading:** Full-screen grille patterns present 50% loading of the display. That may be too much for some technologies. If loading is a factor then use grille patterns that are centered and occupy only 1/9th the area of the screen.
2. **Addressability** states the number of locations at which a pixel (dot) can be displayed on the screen. However, that does not guarantee that the spot of light is small enough to actually *distinguish* adjacent addressable spots.
3. **Resolution** is the number of pixels (or lines) that can be adequately distinguished across the screen.
4. **Contrast modulation (Michelson contrast)** C_M is considered by some to be the best and most complete single-metric description of the ability of a display to exhibit detailed information.
5. **NOTE:** Some displays, as with displays used for television, have their resolution deliberately decreased below the advertised resolution in order to prevent strobing of patterned materials. This does not mean that they are inferior to displays that maintain the highest resolution; it simply is specialized performance setting for a particular purpose.
6. If the display were perfect, the screen would show a series of full white bars with perfectly black bars between them, yielding a C_M of 100 %. In reality, several factors combine to spread the light out so that the pattern is one of light and dark gray bars, not black and white. Among these are:
 - a. The ability of the display to form a narrow line, e.g., problems with crosstalk.
 - b. The accuracy with which the three color beams merge together (in the case of a CRT).
 - c. Halation – the leakage of light from bright areas of the image into the dark areas because of reflections off the covering material, the interior parts of the display, and the display pixel surface.
 - d. A pixel definition based solely on C_M relies only on relative peak and valley luminances independent of absolute luminance. The ANSI pixel defined in ANSI/NAPM IT7-215 limits the allowable luminance rolloff at higher frequencies by requiring the peak luminance of the display at the highest spatial frequency does not degrade below 30 % of the low-frequency peak luminance, specifically that of the 4 x 4 checkerboard pattern. The ANSI pixel modulation is defined as the (peak - valley) luminance of a 1-on/1-off grille relative to the (white - black) luminance of the ANSI large-area 4 x 4 checkerboard test pattern. Using linear interpolation, an estimate of the ANSI pixel can be computed using results obtained by measurement procedures described in § 7.2 Grille Luminance & Contrast and § 5.23 Checkerboard Luminance & Contrast.

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Reporting Results — Sample Data			
Threshold:	25 % (0.25)		
Horizontal		Vertical	
C_{MH} 1x1	0.17	C_{MV} 1x1	0.34
C_{MH} 2x2	0.68	C_{MV} 2x2	0.88
C_{MH} 3x3	0.86	C_{MV} 3x3	0.94
C_{MH} 4x4	0.95	C_{MV} 4x4	0.98
n	1	n	—
n_r	1.157	n_r	1
N_H Native Resolution	1024	N_V Native Resolution	768
Resolution	885	Resolution	768



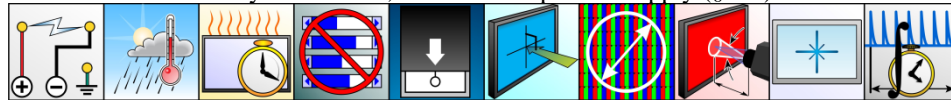
7.9 LUMINANCE STEP RESPONSE

ALIAS: spatial step response

DESCRIPTION: We measure the presence of artifacts caused by overshoots, undershoots, rise time and fall time which may be caused by the video circuitry of a display (e.g., for a CRT display) or the lens of either a projection system or a near-eye display. These characteristics determine the resolution of sharp edges in images on the display. Poor step response will cause streaking of an image on the display. **Units:** none. **Symbol:** none.

APPLICATION: Raster-scanned displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Test target is a square box having an edge size of $0.15 V$ (15 % of the vertical pixel size of the screen) at gray-level $0.90 n$ of the maximum level n (to produce an intended gray shade of 90% L_w , e.g., 229/255 for an eight-bit gray scale), surround by a background at gray-level $0.10 n$ of the maximum level n (to produce an intended gray shade of 10% L_w , e.g., 25/255 for an eight-bit gray scale). Optionally, we can also measure the inverse pattern. For color displays, optionally measure individual primary colored (e.g., red, green, and blue) boxes in addition to white. Scanning or array LMD for revealing horizontal lack of sharpness of box. **NOTE:** Veiling glare in the LMD must be eliminated particularly when you are measuring dark objects on a lighter background; see the appendix, A2 Stray-Light Management & Veiling Glare.

PROCEDURE: Display the target and use a spatially-resolving luminance meter (e.g., CCD array) to measure positive and negative transitions at three equally spaced horizontal lines through the box—see the Fig. 1.

ANALYSIS: Look for noticeable ringing, undershoot, overshoot, or streaking. Use 10% and 90% luminance levels as references for quantifying rise and fall times.

REPORTING: Report the presence of noticeable ringing, undershoot, overshoot, or streaking. Quantify rise and fall times as the distance on the screen required to traverse 10% to 90% luminance levels at the step. Optionally, report rise and fall times in pixel units.

COMMENTS: If possible and the input signal is available, it is useful to photograph (or otherwise preserve) the oscilloscope trace of the video signal generator output (monitor input) to identify any signal artifacts that may be present in the generator—proper signal cabling and termination is required for this measurement. Compare the generator output to the luminance profile of the monitor light output. Artifacts attributable to the monitor are thus separated from the artifacts caused by the video signal generator. It may be important to be aware of the limitation of the LMD used in the event it exhibits sufficient veiling-glare problems to affect the measurement results. See the VESA VSIS standard for additional information regarding the video electrical signal.

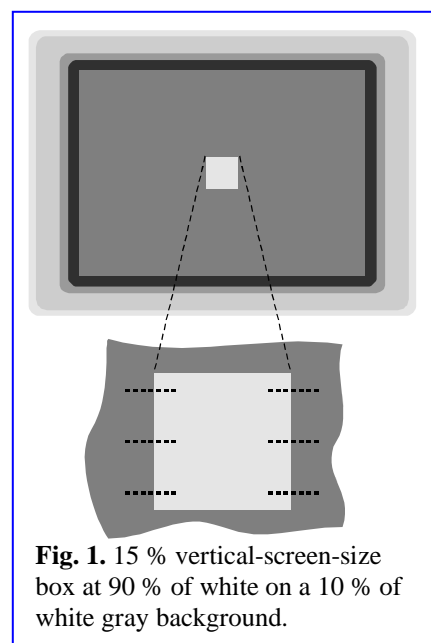


Fig. 1. 15 % vertical-screen-size box at 90 % of white on a 10 % of white gray background.

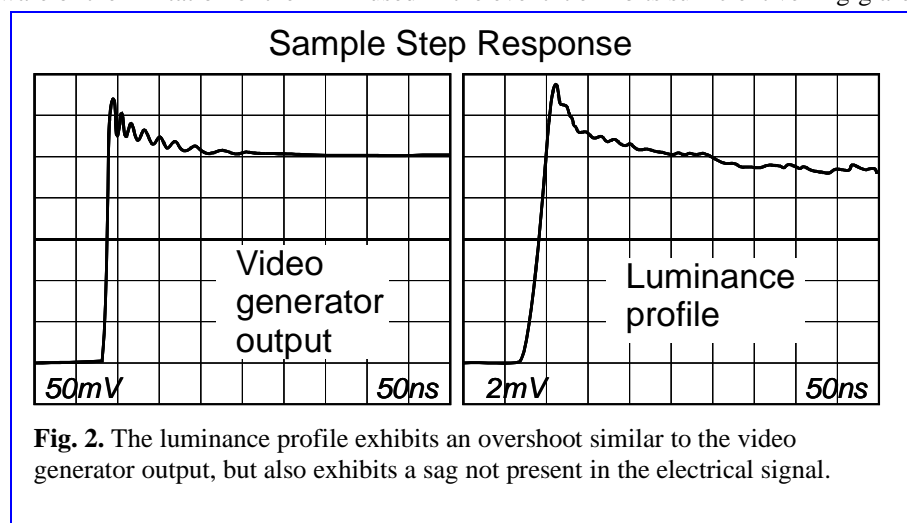


Fig. 2. The luminance profile exhibits an overshoot similar to the video generator output, but also exhibits a sag not present in the electrical signal.

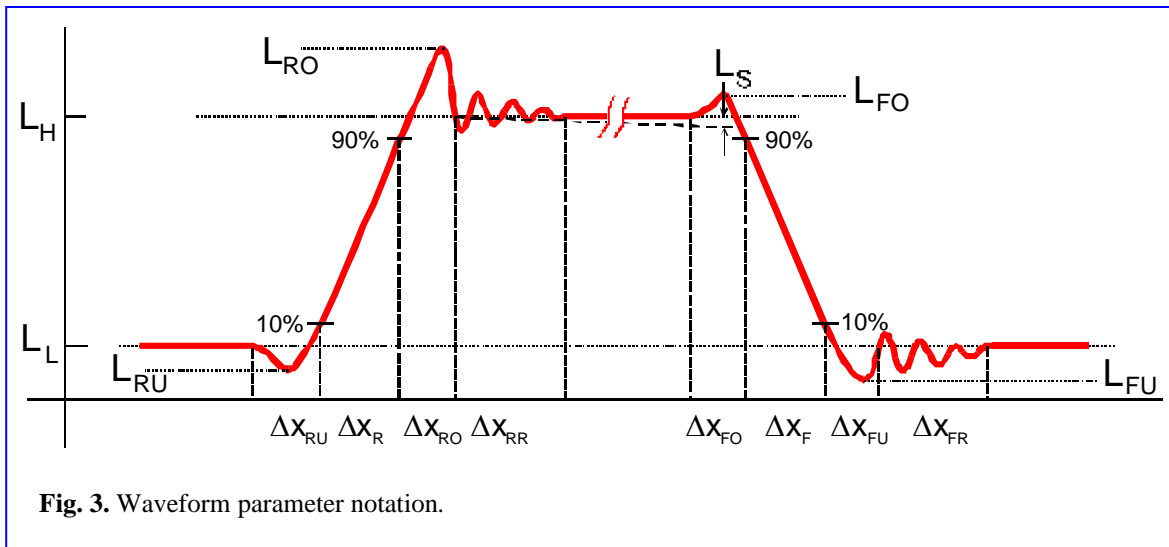


Fig. 3. Waveform parameter notation.

In this notation, the 10 % level means: $L_{10\%} = L_L + 0.1(L_H - L_L)$ and the 90 % level means: $L_{90\%} = L_L + 0.9(L_H - L_L)$.

We speak of rise and fall as if the profile were being painted from left to right as with a scanning display such as a CRT or flying-spot laser display.

L_H = Luminance of higher steady-state level.

L_L = Luminance of lower steady-state level.

L_{RU} = Luminance undershoot on the rising edge.

L_{RO} = Luminance overshoot on the rising edge.

L_S = Luminance sag from L_H .

L_{FO} = Luminance overshoot on the falling edge.

L_{FU} = Luminance undershoot on the falling edge.

Δx_{RU} = Distance from start of undershoot to 10% level.

Δx_R = Distance for 10 % – 90 % rise.

Δx_{RO} = Distance on the rise side from 90 % level to the end of the overshoot at location of L_H after overshoot.

Δx_{RR} = Distance for overshoot ringing settling measured from the end of the overshoot to the point where the amplitude of the luminance ringing is down to $\pm 5\%$ of the final steady-state value L_H .

Δx_{FO} = Distance for overshoot on the falling side from the start of the overshoot to the 90% level.

Δx_F = Distance for 90 % – 10 % fall.

Δx_{FU} = Distance on the fall side from 10 % level to the end of the undershoot at location of L_L after the undershoot.

Δx_{FR} = Distance for undershoot ringing settling measured from the end of the undershoot to the point where the amplitude of the luminance ringing is down to $\pm 5\%$ of the final steady-state value L_L .

NOTE: (1) Measurements from the sag level on the fall side: If there is a sag ($L_S > 0$), then L_{FO} is measured from the sag level as will the 90 % and 10 % levels also be measured relative to the sag level.

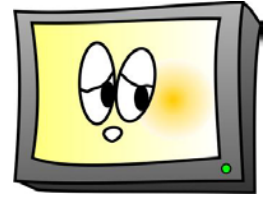
(2) High-level measurement problems: Occasionally, there is a need of filtering to properly measure the high level L_H if a clear high level is not available.

(3) Rise and fall time measurement problems: Because of poor signal quality, it may not always be possible to clearly identify the 10 % and 90 % points on either the rise or fall time. In such cases we measure the 20 %–80 % transition and scale it by a factor of 1.333 (to give an equivalent 10 %–90 % transition) or even the 30 %–70 % transition and scale it by a factor of 2.000 (to give an equivalent 10 %–90 % transition).



8. UNIFORMITY MEASUREMENTS

Usually, what people mean when they say “uniformity” is nonuniformity. Uniformity refers to a metric that characterizes the changes in luminance or chromaticity over the surface of a screen. However, the differences are not the only important thing. The gradient of the luminance shift over the screen is also important. A screen that slowly changes in luminance 20 % over its entire surface would not readily be noticed to the eye. But if that change occurs over a one-degree field of view, it would be noticeable. We start with sampled uniformity because of its simplicity.



Luminance uniformity (or nonuniformity) is a measure of the extent to which the luminance remains constant (or varies) over the surface of the screen. A 100 % uniformity would indicate that the luminance is perfectly uniform across the area of the screen. A 90 % uniformity would indicate that the screen suffers from a small deviation from perfection. We also speak of nonuniformity. A 10 % nonuniformity would mean that the screen is almost perfect. Sometimes people mean nonuniformity when they say uniformity. For this reason, we define both here. Most of the titles in this section refer to uniformity, largely because of tradition. However, the desired metric is usually the nonuniformity. Suppose we measure the luminance at several points on the screen and determine the minimum and maximum luminances L_{\min} and L_{\max} of that sample set. Uniformity \mathcal{U} and nonuniformity \mathcal{N} are then defined as:

$$\mathcal{U} = 100\% \frac{L_{\min}}{L_{\max}}, \quad (1)$$

$$\mathcal{N} = 100\% \frac{L_{\max} - L_{\min}}{L_{\max}} = 100\% \left(1 - \frac{L_{\min}}{L_{\max}} \right). \quad (2)$$

Chromaticity uniformity refers to how well the chromaticity remains constant across the surface of the screen. Conversely, nonuniformity of chromaticity characterizes how the chromaticity varies across the surface of the screen. The nonuniformity of chromaticity is best specified by the maximum chromaticity difference (using some chromaticity difference metric) between any two points on the screen. We recommend the use of the $\Delta u'v'$ chromaticity difference metric, where

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}, \quad (3)$$

where (u'_1, v'_1) and (u'_2, v'_2) are any two chromaticities, and the relationship between the (x, y) chromaticity coordinates and the (u', v') coordinates is

$$u' = \frac{4x}{3 + 12y - 2x}, \quad v' = \frac{9y}{3 + 12y - 2x}. \quad (4)$$

At constant luminance, two adjacent color patches can usually be distinguished with a $\Delta u'v' \geq 0.004$, but for spatially separated colors, a shift of $\Delta u'v' \geq 0.04$ is often required to notice a difference (see appendix B1 Radiometry, Photometry, and Colorimetry).

Sampled vs. Area Uniformity: There are at least two types of uniformity: sampled uniformity and area uniformity. Sampled uniformity refers to comparing several discrete points on the screen and provides a quick check of the uniformity. Area uniformity requires the use of a scanning or array LMD to obtain a measure of the uniformity for the entire display surface.

Sampled Uniformity: There are several ways to define sampled uniformity for **luminance**: (1) Determine the largest deviation from the average: If $L_{\text{ave}} - L_{\min} > L_{\max} - L_{\text{ave}}$ then use $\Delta L = L_{\min} - L_{\text{ave}}$ otherwise let $\Delta L = L_{\max} - L_{\text{ave}}$ (this is the extreme value; it will preserve the sign of the greatest deviation). The nonuniformity could then be expressed by $100\% \Delta L / L_{\text{ave}} \equiv 100\% \max |L_i - L_{\text{ave}}| / L_{\text{ave}}$. (2) Base the nonuniformity on the average value $100\% (L_{\max} - L_{\min}) / L_{\text{ave}}$, or (3) the standard deviation $100\% \sigma_L / L_{\text{ave}}$, where σ_L is the standard deviation of the L_i for $i = 1, 2, \dots$ (4) Base the nonuniformity on the center measurement $100\% \max |L_c - L_i| / L_c$. (5) Base the nonuniformity on the deviation from the maximum $100\% (L_{\max} - L_{\min}) / L_{\max}$. The working group felt that this last measure of sampled nonuniformity was the most natural representation of sampled uniformity. We would suggest that this measure of uniformity, using five points, be employed when displays are compared based upon a sampled uniformity.

For **chromaticity**, the maximum chromaticity difference $\Delta u'v'$ between the most separated sampled pair of patches must be determined. You might be able to avoid having to calculate the chromaticity difference metric for all the sampled



pairs if you graph the (u', v') chromaticities and are able to clearly select the largest separation between any two sampled patches. If it is obvious which pair is furthest apart, the maximum chromaticity difference is $\Delta u' v'$ for that pair. If it is difficult to clearly identify the greatest separation, graphing will at least help in selecting the most likely pairs, otherwise $\Delta u' v'$ will have to be calculated for all pairs and the maximum determined.

Weighted Sampled Uniformity: There may be a reason for weighing the sampled uniformity measurement so that more emphasis is placed on the center of the screen. Again, such a change is acceptable provided that all interested parties are in agreement with the modified procedure. In such a case we would define weights $w_i \leq 1$ associated with each sampled position i . For example, at each sampling point, a luminance measurement is made L_i . An average value for all luminances is determined L_{ave} (or the center value could be used), and a new set of modified luminances L_i' are calculated:

$L_i' = L_{ave} + w_i (L_i - L_{ave})$. The nonuniformity, or uniformity, would then be determined based upon this new set of weighted luminances. This kind of scheme might be used for displays where the most important areas are at the center of the screen and nonuniformities at the edges of the screen are of less importance. Whatever weighing scheme is used, all interested parties must agree to the use of such uniformity metrics, and any reporting documentation must clearly state the modified procedure.

Other Sampling Schemes: We illustrate a symmetrical sampling of the screen using five or nine points. *The committee suggests that a nine-point sampled uniformity based on the maximum luminance be used for comparisons between displays.* This is a suggestion. There may be important reasons for using other schemes, five point, 25 point, centers of a 3×3 rectangular grid, etc. Other sampling schemes are allowed provided it is made clear in any reporting document and all interested parties agree to such modifications to the procedures. For example, one way is to divide the screen into small squares along a diagonal, one of which includes the center, along with a square in each corner of the screen. The brightest, the dimmest, and the center measurement sample points in the uniformity measurement will be used in the uniformity testing—a three point sampled uniformity. There is no objection to doing this. Simply use the same procedure with the new locations. See the ISO 13406 standard.

Combinations: Combinations of sampled uniformity measurements and other measurements are possible. For example, you might be interested in the uniformity at certain viewing directions. This would mean making a viewing direction measurement at the uniformity sampling points. Such combinations are straightforward applications of two procedures in this document.

Vantage Point, Viewing Point, or Design

Viewing Direction: See Fig. 1 that shows the vantage point simulating a between-the-eyes viewing point. In many of the measurements in this standard, the view from the perpendicular of the flat screen surface is utilized as the measurement direction. This may not always be the type of uniformity measurement that is useful for certain displays and certain tasks. A display might look very uniform from infinity (all views perpendicular from the screen, similar to a distant viewer using a telescope to see the screen), but not have nearly the same uniformity when viewed from a typical reading distance 30 cm to 50 cm away from its center as with computer monitors and at a normal viewing distance, similarly for entertainment viewing such as TV. Thus, a sampled uniformity or area uniformity may be more meaningful if the luminance (or chromaticity) of the display is measured through a vantage point, also called a viewing point or design viewing point. That is, the configuration of the LMD and the display is arranged so that the LMD is always viewing through the same point in space located at a specified direction from the normal of the screen and at a specified distance from the screen. See Fig. 2 for a comparison of having the LMD normal to the screen and the use of a vantage point.

The problem in making vantage-point measurements with spot-meter LMDs (one that makes its measurements at only one location) is that achieving the arrangement as in Fig. 2b can be very difficult—always measuring through the same point in space. Most often, unless they have an expensive positioning apparatus, people end up mounting the spot meter on a

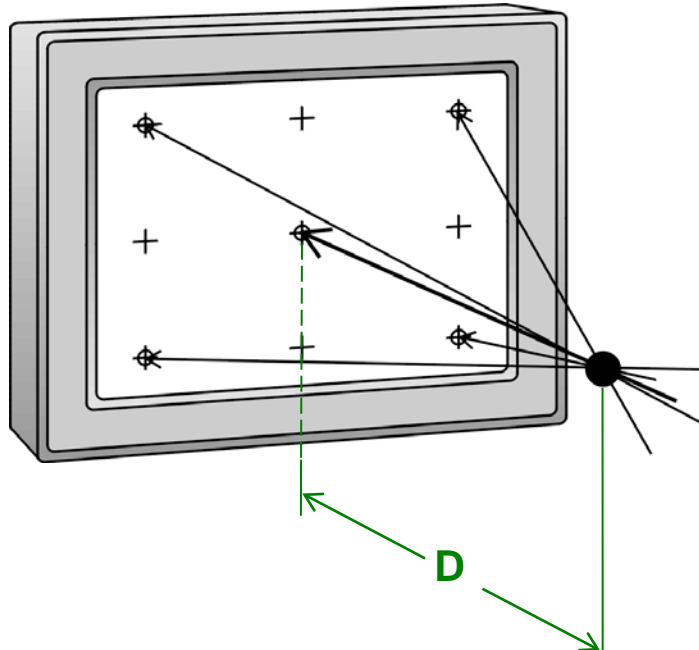


Fig. 1. Vantage-point distance D and measurement directions for five selected measurement locations.



tripod, setting the proper distance to the screen center so that the center measurement is looking through the vantage point, and then using the tripod to point at the desired measurement locations. This is not the same situation where we always measure through the same vantage point—see Fig. 3 and compare it with Fig. 2b. Whereas the spot meter makes the center measurement through the vantage point, other orientations will not be through the vantage point unless the tripod is moved and repositioned. Just rotating the tripod head will not place the spot meter measuring through the vantage point. We are by no means insisting that a tripod not be used. We want you to be aware of the ideal vantage-point measurement illustrated in Fig. 2b and how it is different than the easier tripod method illustrated in Fig. 3. There may be situations in which there is a difference in the measurement results so that you will desire to use the more correct measurement configuration in Fig. 2b to make your vantage-point measurements.

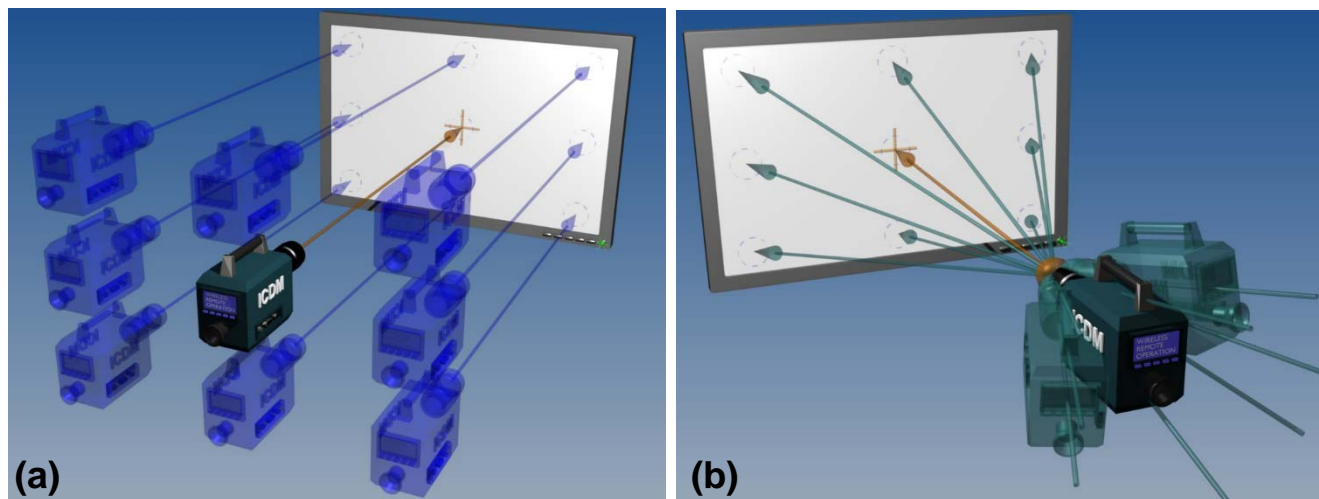


Fig. 2. Illustration of two different configurations for sampled uniformity measurements in nine locations: (a) all measurement taken normal to the screen (an infinity observer), and (b) all measurements taken through the vantage point (not all positions of the LMD are shown to maintain clarity of the image), where the orange ball just in front of the lens of the LMD represents the vantage point.

Measurement Distance: When performing vantage point measurements or measurements with an imaging colorimeter, which effectively is a high-resolution vantage point measurement, one must choose a measurement distance since the measurement results can depend on the distance. Our standard measurement distance of 500 mm may not always be suitable. *If a distance other than 500 mm is used, it must be reported to all interested parties.* There is a variety of displays that have widely different design viewing distances, from mobile phones to large screen televisions or projection systems. For televisions, a larger distance may be required; the suggested method of choosing a proper measurement distance that is independent of the type of display is based on a limit of the average human visual acuity, which corresponds to 48 pixels/degree of visual angle (others have used 60 px/degree for excellent vision of bright targets, see references below). To convert this resolution limit to a distance, $D = 48P/\tan(1^\circ) = 2750 P$, where P is the pixel size assuming square pixels. (For 60 px/degree, $D = 60P/\tan(1^\circ) = 3437 P$.) As an example, a full HD display has a resolution of 1920x1080 pixels. Applying the 2750 pixel distance would indicate a measurement distance that is 2.54 times the screen height V , $D = (2750/1080) V$, which is a typical working distance for a television (60 px/degree will give approximately 3.18 screen heights). **References:** For 48 px/degree see Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, pp. 7.1-7.56). New York: Wiley; for 60 px/degree with very bright targets see, e.g., *The Encyclopedia of Medical Imaging*, H. Pettersson, Ed., p. 199. Taylor & Francis, UK, 1998.

Average Values: The averages calculated are the average of the data obtained. It will often be the case that any metric calculated using the average values will be different from the average value of the metric applied to each sampling

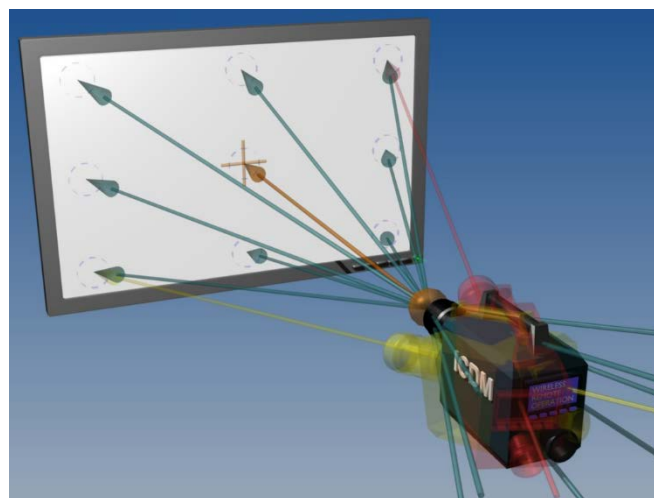


Fig. 3. Vantage-point measurement attempt as would occur by mounting the spot-meter LMD on a tripod.



position. That is, the average of the contrast ratios calculated for each point $(1/N)\Sigma(L_{wi}/L_{ki})$ will, in general, not be equal to the contrast ratio of the averages $(1/N)\Sigma L_{wi}/\Sigma L_{ki}$. In our examples this amounts to noting that the column averages cannot be directly cross correlated along the rows. As another example, consider the (x_i, y_i) chromaticity coordinate that determine the color temperature of each sample point T_i . The average of the (x, y) values (x_{ave}, y_{ave}) do not, in general, provide the same color temperature as the average of the color temperatures for all the sample points. [See the definition of CCT in the Glossary for a method to determine CCT from the chromaticity coordinate (x, y) .]

Area Uniformity: Some equipment can capture an image of the entire display surface using an array detector or high-quality camera that is suitable for this purpose—See Fig. 4. Such equipment must be flat-field corrected for the lens and apparatus configuration employed (sometimes focus distance, f/stop, exposure, relative size of illuminated area to the array size, and any filtration employed can affect the flat-field correction that needs to be used—see the appendix § A9 Array-Detector Measurements for more discussion of imaging systems). The advantage of such array luminance meters and colorimeters is that they not only replicate a vantage-point measurement, but they also provide a detailed mapping of the display surface so that a large number of imperfections can be characterized. To supplement the use of array detectors, we have included a section on area uniformity measurements with a detailed *mura* measurement method. Mura is a low-contrast non-uniformity, usually with low spatial frequency content.

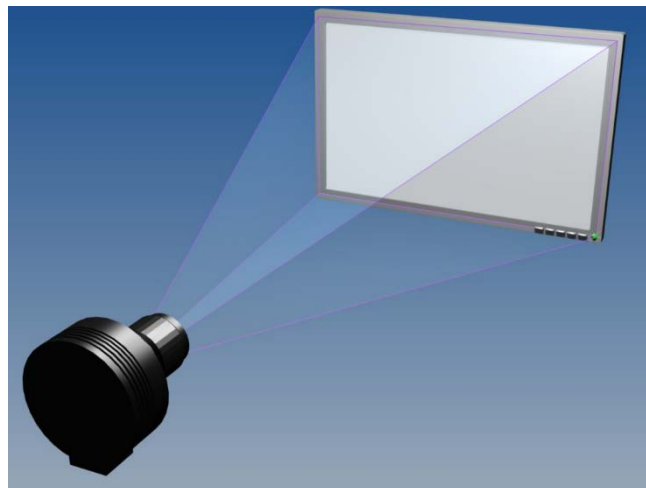


Fig. 4. Array detector that captures the entire screen pattern in one image.

ERGONOMICS, VISION SCIENCE,
AND PSYCHOPHYSICS IN SOME HANDS
CAN BE A DANGEROUS THING!



RUSTIC METROLOGY

For the record: 1:100 is what the eye *instantaneously* can see. The dynamic range is much larger—huge! See the HDR Tutorial B33.

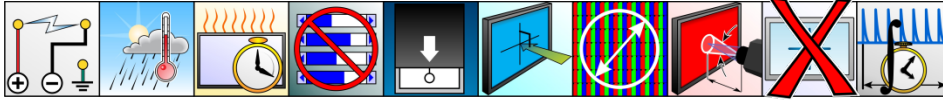
Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



8.1 SAMPLED UNIFORMITY

DESCRIPTION: Measure the luminance and chromaticity coordinates of a display at sampled locations to determine the overall uniformity of the display while showing a full screen pattern: white, black, gray shade, or some color. **Units:** none. **Symbol:** \mathcal{U} for uniformity, \mathcal{N} for nonuniformity.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Prepare to measure five or nine points on the screen for the required full-screen pattern. The points are arranged in an X or 3x3 array, with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (see the figure). For example, if the screen is 100 cm wide and 80 cm tall, the edge points would be located 10 cm inward from the right and left edges and 8 cm inward from the top and bottom edges. All points should be measured with the LMD normal to the screen, so the LMD or the display should be translated to move from one measurement point to the next. The points are numbered left-to-right and top-to-bottom as one would read English.

PROCEDURE: At each location measure luminance and chromaticity values of the full-screen pattern at the five or nine points. Make sure that the LMD is normal to the screen at each measurement point.

ANALYSIS:

- For each full-screen pattern find the minimum L_{\min} and maximum L_{\max} luminance values of the set of five or nine measured points.
- Calculate the nonuniformity for that full-screen pattern:

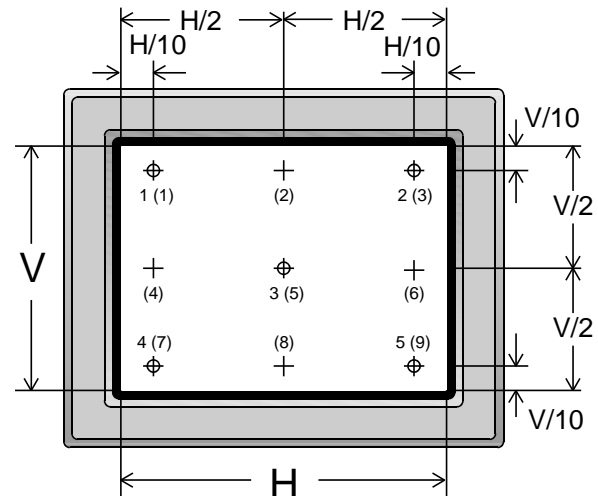
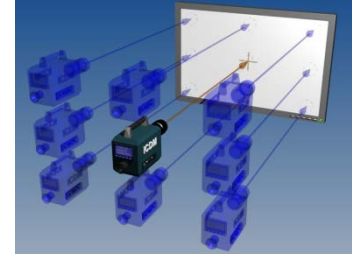
$$\mathcal{N} = 100\% \left(1 - \frac{L_{\min}}{L_{\max}} \right). \quad (1)$$

- To calculate the uniformity of the chromaticity for each selected luminance level, find the u' and v' coordinates of each measured point. Find the two points that are farthest apart on a $u'v'$ -graph, by using equation (2) to compare chromaticity differences between all 10 or 36 combinations of two points and report the largest value. Alternatively, the u' and v' points can be graphed to visually determine which pair is most separated, and $\Delta u'v'$ is still calculated:

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}. \quad (2)$$

REPORTING: Report whether five or nine samples are measured. Report the nonuniformity at each selected luminance level as a percentage to no more than three significant figures. Report the maximum chromaticity difference at each selected luminance level to no smaller uncertainty than ± 0.01 .

COMMENTS: For some types of displays, such as those with dynamic backlights, the luminance levels might need to be adjusted. For example, black uniformity might be meaningless, but more levels of low-luminance data may be collected. Uniformity for $L_{\max}=0$ is 100%, Keep in mind the difference between the input gray level and the associated luminance of the resulting gray shade. For example, an input gray level of 127 out of 256 does not produce 50% of the luminance of white!



⊕ Denote 5-point locations. + Denote 9-point locations.
1, 2, 3, 4, 5 (1), (2), (3), ..., (9)

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting Example (Sample Data)

9-Point Luminance and Color Nonuniformity (Normal View)

Luminance	Nonuniformity, \mathcal{N}	$\Delta u'v'$
White (100%)	30%	0.005
Gray (20%)	35%	0.008
Dark Gray (5%)	55%	0.011
Custom(3%)	45%	0.009
Black (0% input)	40%	0.007



8.1.1 SAMPLED CONTRAST UNIFORMITY

DESCRIPTION: Calculate the luminance contrast ratio at each of the five or nine points measured in § 8.1 for a white screen and a black screen. **Units:** none for contrast ratio, percent for uniformity of contrast ratio. **Symbol:** \mathcal{N}_C .

SETUP: None. This calculation uses the data from § 8.1.

PROCEDURE:

1. Collect white and black luminance data for five or nine points as per § 8.1.
2. For each of the five or nine points, calculate a contrast ratios C_i :

$$C_i = \frac{L_{Wi}}{L_{Ki}}. \quad (1)$$

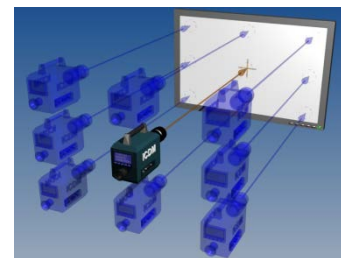
ANALYSIS:

1. Find the minimum and maximum contrast ratios $C_{\min} = \min(C_i)$ and $C_{\max} = \max(C_i)$, $i = 1, 2, \dots$ of the set of measured points.
2. Calculate the nonuniformity:

$$\mathcal{N}_C = 100\% \left(1 - \frac{C_{\min}}{C_{\max}} \right). \quad (2)$$

REPORTING: Report the number of samples used. Report C_{\min} and C_{\max} , and the nonuniformity to no more than three significant figures. Report the nonuniformity in percent.

COMMENTS: See comments of § 8.1.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

**Reporting example (Sample Data) –
9-Point Contrast Nonuniformity
(Normal)**

Maximum, C_{\min}	800
Minimum, C_{\max}	600
Nonuniformity, \mathcal{N}	25%

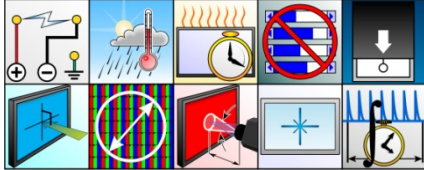


8.1.2 SAMPLED VANTAGE-POINT UNIFORMITY

DESCRIPTION: Measure the luminance and chromaticity coordinates of full-screen white, black, and gray levels at five or nine points. The luminance nonuniformity is reported in percent deviation from the maximum value measured at each luminance level.

The maximum chromaticity difference is reported as $\Delta u'v'$. This test measures the luminance uniformity of the screen viewing each sampled point from the same direction as a human observer would do. **Units:** percent for luminance nonuniformity, and no units for $\Delta u'v'$ chromaticity difference. **Symbol:** none.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

Full-screen white test pattern (100% luminance), full-screen gray test pattern (20% luminance), full-screen dark gray test pattern (5% luminance), and full-screen black test pattern (0% input gray level). The same five or nine points are measured at each luminance level. The points are arranged in an X or 3x3 array and numbered left-to-right and top-to-bottom as one would read English. The edge points are located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points are centered between the edges (See Figure). For example, if the screen is 100 cm wide and 80 cm tall, the edge points would be located 10 cm inward from the right and left edges and 8 cm inward from the top and bottom edges. All points should be measured with the LMD peering through the same imaginary point in space at a position of the correct distance. There are two options for the distance:

1. Near field - wide angles: This standard distance in this document is 50 cm. Some prefer a shorter viewing distance of 30 cm (or the shortest focal distance of the LMD beyond 30 cm) to provide large measurement angles and more critically view the uniformity characteristics at the various directions. Making this measurement with an imaging LMD requires a wide-angle lens to achieve the same angle views at such short distances that a spot LMD achieves when it pivots at a close distance to the display.
2. Far field - narrower angles: Distance which corresponds to the visual acuity limit of an average user. To calculate the distance between the LMD and the screen, find the size of a screen pixel $P = V/N_V$ and multiply that size by 2750:

$$D = 2750 V/N_V = 2750 P, \quad (1)$$

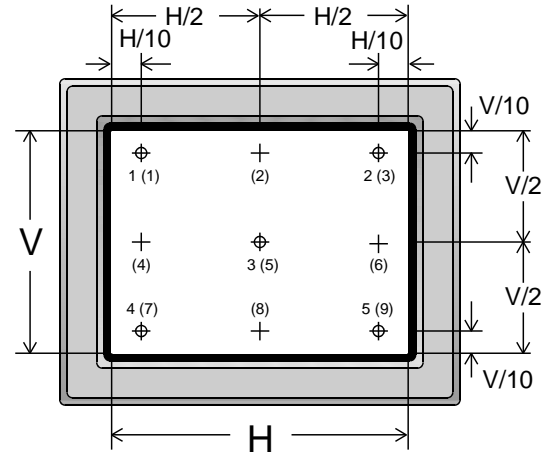
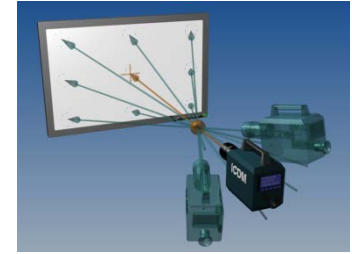
where P is the pixel pitch (assuming square pixels), V is the vertical screen height, and N_V is the number of pixels in the vertical direction. Use of this distance will give more gradual angles to the corners and will show less variations among the measured spots. See § 3.2.8 for more information on the determination of D .

PROCEDURE:

1. Locate the LMD at the correct viewing distance imaged on the center point per one of the two options given.
2. Measure the luminances and chromaticity coordinates for five or nine screen locations. The LMD must remain at approximately the same distance from the screen and pivot to measure through the imaginary point D . If the LMD is a flat-field compensated imaging colorimeter, all five or nine points may be measured at the same time at position D .

ANALYSIS:

1. At each luminance level, find the minimum and maximum luminance values of the set of five or nine measured points.
2. Calculate the nonuniformity at that luminance level:



⊕ Denote 5-point locations. 1, 2, 3, 4, 5
+ Denote 9-point locations. (1), (2), (3), ..., (9)

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example (Sample Data) 9-Point Luminance and Color Nonuniformity (Vantage Point)

Luminance	Nonuniformity \mathcal{N}	$\Delta u'v'$
White (100%)	30%	0.005
Gray (20%)	35%	0.008
Dark Gray (5%)	55%	0.011
Custom(3%)	45%	0.009
Black (0% input)	40%	0.007



$$\mathcal{N} = 100\% \left(1 - \frac{L_{\min}}{L_{\max}} \right) \quad (2)$$

3. To calculate the chromaticity uniformity for each luminance level, find the u' and v' coordinates of each measured point. Find the two points that are farthest apart on a $u'v'$ -graph, by using Eq. (2) to compare chromaticity differences between all 10 or 36 combinations of two points, and report the largest value. Alternatively, the u' and v' points can be graphed to visually determine which pair is most separated and $\Delta u'v'$ is still calculated:

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2} \quad (2)$$

REPORTING: Report whether five or nine samples are measured. Report the nonuniformity at each luminance level as a percentage to no more than three significant figures. Report the maximum chromaticity difference at each luminance level to no smaller uncertainty than ± 0.001 .

COMMENTS: (1)**Dynamic Backlights:** For some types of displays, such as those with dynamic backlights, the luminance levels might need to be adjusted. For example, black uniformity might be meaningless, but more levels of low-luminance data may be collected. (2)**Luminance vs. Gray Value:** Keep in mind the difference between the input gray level and the associated luminance of the gray shade. For example, an input gray level of 127 out of 256 does not produce 50% of the luminance of white!

8.1.3 SAMPLED VANTAGE-POINT CONTRAST UNIFORMITY

DESCRIPTION: Calculate the luminance contrast ratio at each of the five or nine points measured in § 8.1.2. **Units:** none for contrast ratio, percent for uniformity of contrast ratio.

Symbol: C_U .

SETUP: None. This calculation uses the data from § 8.1.2.

PROCEDURE:

1. Collect white and black luminance data for 5 or 9 points as per § 8.1.2.
2. For each of the 5 or 9 points, calculate a contrast ratio as per equation (1).

$$\text{Contrast ratio } C_U = \frac{L_{\text{White}}}{L_{\text{Black}}} \quad (1)$$

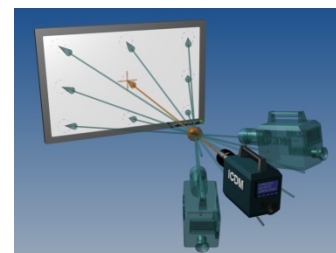
ANALYSIS:

1. Find the minimum and maximum contrast ratios (C_{\min} and C_{\max}) of the set of measured points.
2. Calculate the nonuniformity using this equation:

$$\text{Nonuniformity: } \mathcal{N} = 100\% \left(1 - \frac{C_{\min}}{C_{\max}} \right) \quad (2)$$

REPORTING: Report the number of samples used. Report C_{\min} and C_{\max} , and the nonuniformity to no more than three significant figures. Report the nonuniformity in percent. Report the maximum color difference to no smaller uncertainty than ± 0.001 .

COMMENTS: See comments of § 8.1.2.



—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example (Sample Data) 9-Point Contrast Ratio Nonuniformity (Vantage Point)	
Maximum, C_{\max}	800
Minimum, C_{\min}	600
Nonuniformity, \mathcal{N}	25%



8.2 AREA UNIFORMITY

DESCRIPTION: Measure the luminance and chromaticity coordinates of full-screen white, black, and gray levels at an array of thousands of points, typically with an imaging colorimeter. The resulting data is used to create an image so that image analysis techniques may be applied to locate and quantify low-contrast, slowly varying localized nonuniformities, sometimes referred to as *mura*. The analysis of the data is described in § 8.2.2 and § 8.2.3. **Units:** none. **Symbol:** none.

APPLICATION: All displays.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Full-screen white test pattern (100% luminance), full-screen gray test pattern (20% luminance), full-screen dark gray test pattern (5% luminance), and full-screen black test pattern (0% luminance). The measurement of the screen will be taken from a single vantage point at a distance of 2750 display pixels normal to the center of the screen. (The number 2750 is discussed in the procedure below. See the discussion of measurement distance in the uniformity introduction should you wish more information.) The easiest way to perform this measurement is with an imaging colorimeter. If using an imaging colorimeter, its horizontal or vertical pixel count should be at least 50% of the horizontal or vertical pixel count of the screen. It may be possible to perform this measurement with a spot meter, in which case the number of points measured should be at least half as many in each direction as there are pixels in the display, and the area of the measured points should not overlap. The result of the measurement will be an image of thousands or millions of pixels of luminance and chromaticity data. For example, if the screen is 1280 pixels by 800 pixels, then the result of this measurement should be an image at least 640 pixels by 400 pixels.

PROCEDURE:

1. To calculate the correct distance between the LMD and the screen, first find the size of a screen pixel $P = V/N_V$ and multiply that size by 2750:

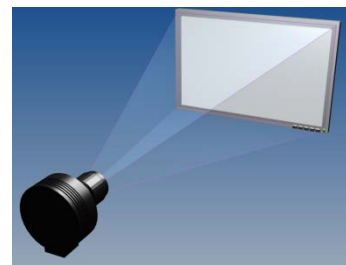
$$D = 2750 \text{ V}/N_V = 2750 P, \quad (1)$$

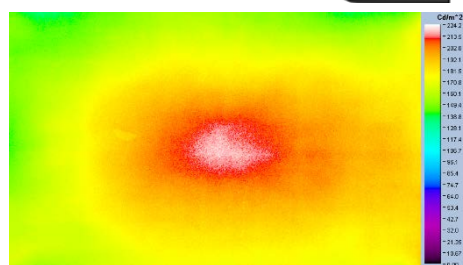
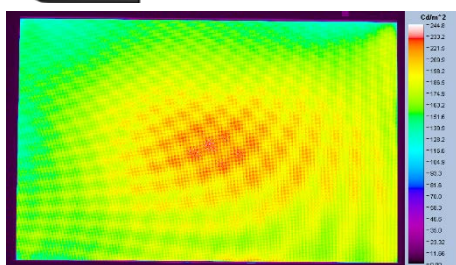
where P is the pixel pitch (assuming square pixels), V is the vertical screen height, and N_V is the number of pixels in the vertical direction. See § 3.2.8 for more information on the determination of D .

2. Place the LMD at this distance in front of the screen. If using an imaging colorimeter, adjust it so that an area slightly larger than the entire screen is captured to ensure that defects near the edges of the screen can be located. If using a spot meter, it is important to rotate it toward each point instead of translating it (as you would in making vantage-point measurements).
3. Set the screen to one of the full-screen test patterns. Measure an array of points that is an appropriate resolution as per the setup conditions above.
4. Repeat step 3 for the other test patterns.
5. If desired, the screen may be rotated around its centered vertical or horizontal axis and measured in the same way to identify other types of defects at different viewing directions. In this case, the distance from the center of the screen should remain the same.

ANALYSIS:

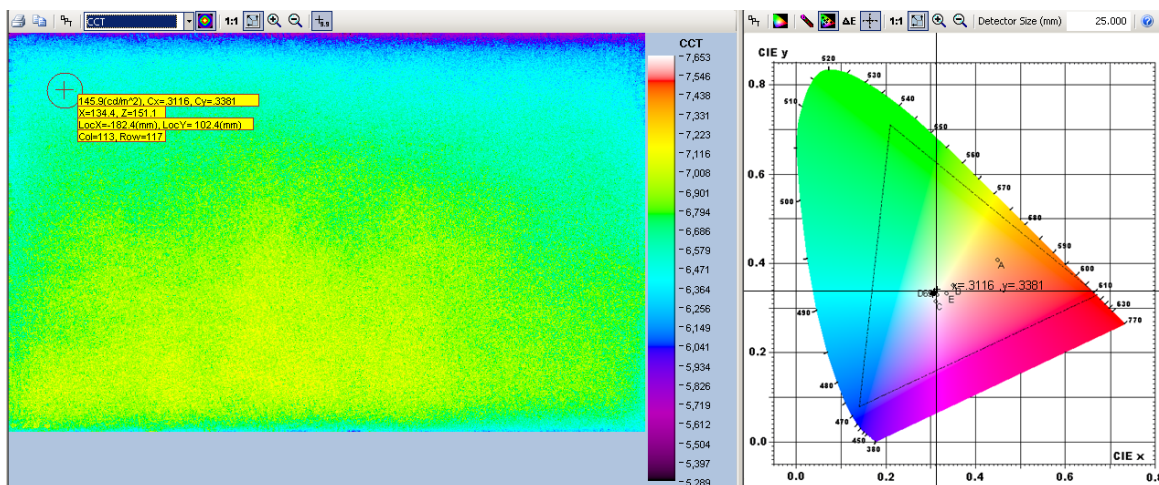
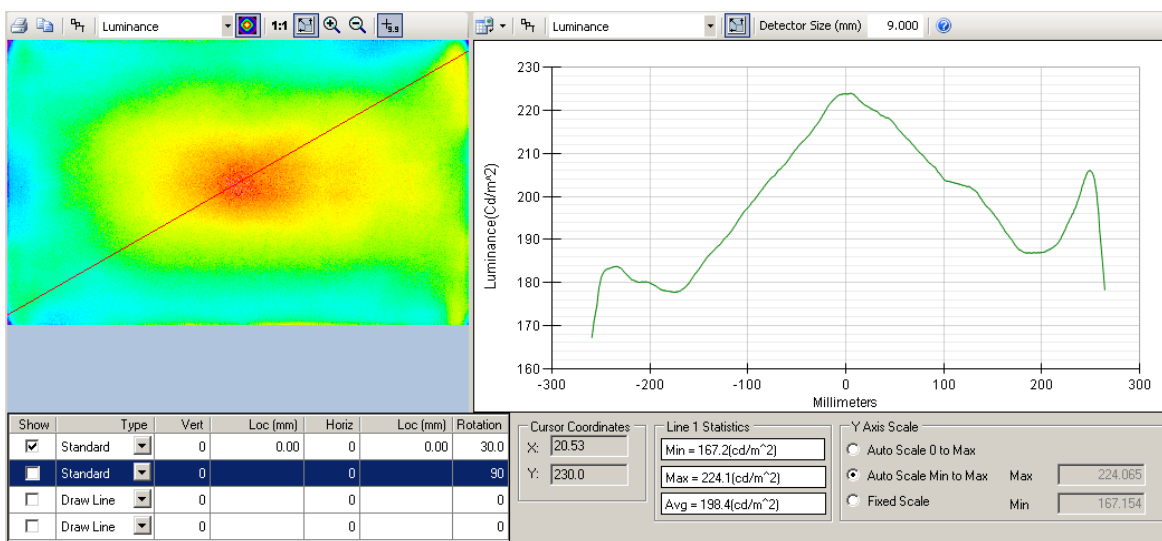
1. If the image of the display is rotated within the field-of-view of the camera, rotate the LMD around its optical axis and/or perform image processing to make the camera and display pixel arrays parallel to each other.
2. Crop the image to remove border pixels corresponding to areas outside the edge of the display.
3. If moiré patterns appear in the image, they must be removed before the image can be processed for defects (see image below). This can be achieved by defocusing the imaging colorimeter slightly, applying an optical low-pass filter, selectively deleting appropriate high-frequency spikes from a 2-dimensional Fourier transform of the image, or by rotating the display slightly about the line between the imaging colorimeter and the screen center. Care must be taken to avoid removing actual screen nonuniformities from the image during this process.

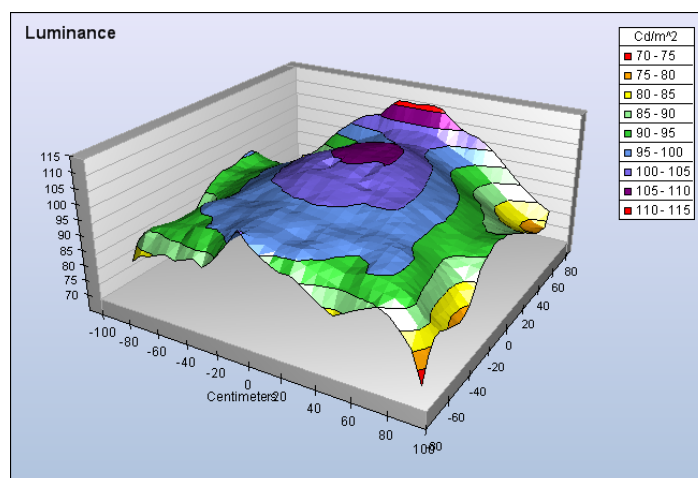




REPORTING: The data taken using this procedure is not reported directly. Instead, it is analyzed using techniques in Standard 8.2.2 Area Uniformity Statistical Analysis to reveal nonuniformities in a way that corresponds to how humans perceive them.

COMMENTS: Note that if the array detector is placed at the vantage point (design viewing point, viewing point) then it can serve as a detector for vantage-point measurements outlined in the previous sections.





8.2.1 AREA CONTRAST UNIFORMITY

DESCRIPTION: Calculate the contrast ratio at each pixel measured in § 8.2.

Units: none for contrast ratio, percent for uniformity of contrast ratio. **Symbol:** C_U .

SETUP: None. This calculation uses the data from § 8.2.

PROCEDURE:

1. Collect white and black luminance data for the screen as per § 8.2.
2. Make sure that the black and white images have the same number of pixels, and that pixels at corresponding locations in each image correspond to the same location on the screen.
3. For each recorded pixel, calculate a contrast ratio as per equation (1).

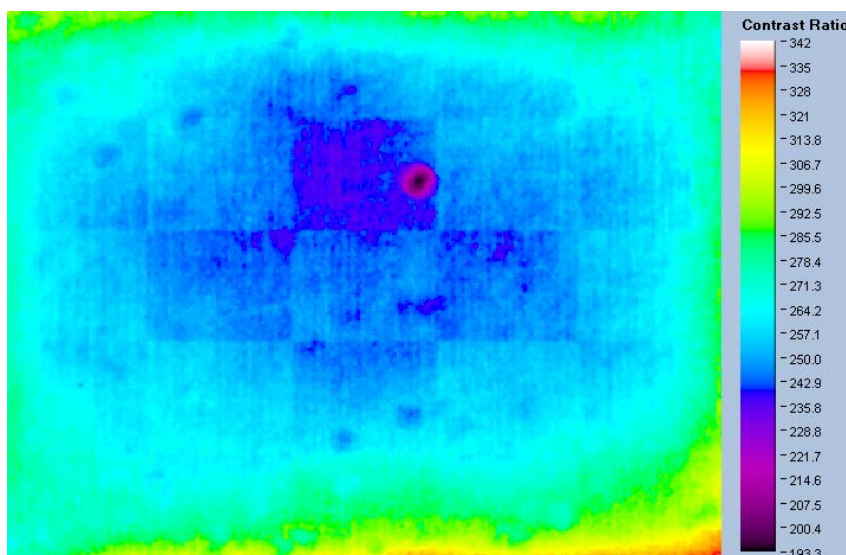
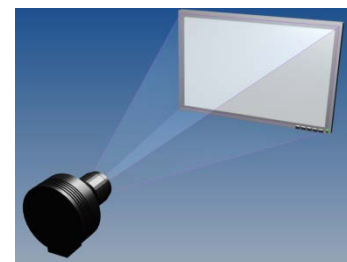
$$\text{Contrast ratio } C_U = \frac{L_W}{L_K} \quad (1)$$

4. Create a resulting image from the contrast ratios at each camera pixel.

ANALYSIS: See § 8.2.2 and § 8.2.3 following this section.

REPORTING: This procedure is used to acquire data that can be analyzed using techniques from § 8.2.2. As such, there is nothing to report for this measurement.

COMMENTS: None.





8.2.2 AREA UNIFORMITY STATISTICAL ANALYSIS

DESCRIPTION: This test is a statistical evaluation of the data from § 8.2 Area Uniformity and § 8.2.1 Area Contrast Uniformity. **Units:** cd/m² for luminance, percent for percent deviation. **Symbol:** L_{RMS} .

APPLICATION: All displays.

SETUP: None. This test uses the data gathered in § 8.2 and calculations in § 8.2.1.

ANALYSIS:

1. Collect the luminance measurements from § 8.2.
2. For each image, calculate the root mean square (RMS) luminance of the screen. To do this, square the luminance values of each pixel, total these values, divide by the number of pixels, and take the square root of the answer:

$$\text{RMS Luminance: } L_{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^n L_i^2} \quad (1)$$

3. For each image, find the luminance values of the pixels with maximum and minimum luminance.
4. Calculate the maximum deviation ΔL_{\max} expressed in percent:

$$\text{Maximum deviation: } \Delta L_{\max} = 100\% \left(1 - \frac{L_{\min}}{L_{\max}} \right) \quad (2)$$

5. For each image, find the difference between the RMS value and the maximum, and between the RMS value and the minimum, and report the larger difference as the Maximum Deviation from the Mean.
6. Repeat steps 2-5 with the contrast ratio image from § 8.2.1 Area Contrast Uniformity.

REPORTING: For each image, report the RMS Luminance of the screen, the maximum and minimum luminance values, the Maximum Percent Deviation, and Maximum Deviation from the Mean. Report the luminance values to no more than 3 significant figures, and the percent values to no more than 2 significant figures.

Reporting example (Sample data) Area Statistical Analysis					
Pattern →	White (100%)	Gray (20%)	Dark Gray (5%)	Black (0%)	Contrast
RMS Luminance, L_{RMS}	100 cd/m ²	20.7 cd/m ²	4.95 cd/m ²	1.43 cd/m ²	69.9
Maximum luminance, L_{\max}	151 cd/m ²	30.1 cd/m ²	7.99 cd/m ²	3.00 cd/m ²	130
Minimum Luminance, L_{\min}	50.0 cd/m ²	10.5 cd/m ²	2.95 cd/m ²	0.5 cd/m ²	47.0
Maximum deviation from the mean:	51.0 cd/m ²	10.6 cd/m ²	3.04 cd/m ²	1.57 cd/m ²	59.9
Maximum deviation ΔL_{\max} (%)	66 %	65 %	63 %	83 %	64 %

COMMENTS: None



8.3 MURA ANALYSIS

DESCRIPTION: This test uses the data from § 8.2 Area Uniformity and § 8.2.1 Area Contrast Uniformity to find defects (called mura) visible to a standard human observer by applying a contrast sensitivity function. **Units:** Just noticeable difference (JND) or luminance just noticeable difference (LJND). **Symbol:** none.

SETUP: None. This test uses the data gathered in § 8.2.

ANALYSIS:

1. Collect the measurements from § 8.2. Care must be taken to avoid moiré in the original captured image or the Moiré must be removed as previously described.
2. Convert the image to relative luminance. An example is shown in Fig. 1. A contrast-enhanced version is also shown. Several low-contrast blemishes (mura) can be seen near the middle of the screen. Note also the darkening near the upper edge. This test image has dimensions of 900 x 1200 px. In this example we assume it is viewed a distance such that the visual resolution is 48 px/deg. This corresponds to a viewing distance of 2750 image pixels. See § 3.2.8 for more information on the determination of D .

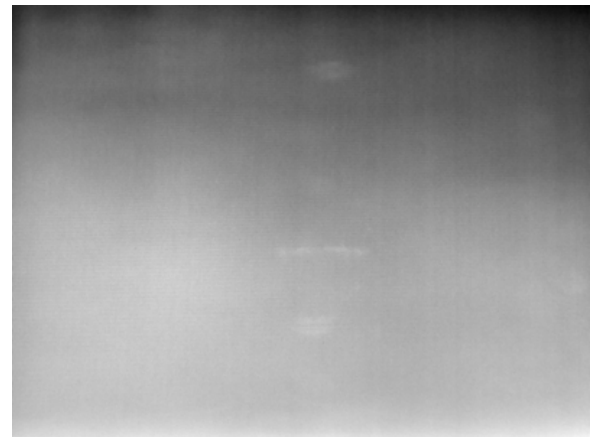
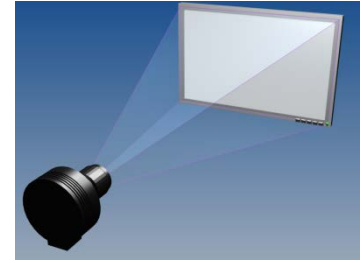


Fig. 1. A captured image of the screen of the DUT: a) actual image, b) contrast-enhanced.

3. Pre-filter and down-sample the image to reduce noise and subsequent computation. In this example we use a Gaussian pre-filter whose kernel can be written

$$G(i, j) = \exp\left(-\pi \frac{i^2 + j^2}{s^2 r^2}\right), \quad (1)$$

where i and j are row and column, s is the Gaussian scale in deg, and r is the visual resolution in px/deg. The scale of a Gaussian kernel is the distance in which it falls to $e^{-\pi}$. Here we use a scale of 1/8 deg, and recall that $r = 48$ px/deg. The kernel must be large enough to accommodate most of the non-zero part of the kernel, in this case $2s$, or 12 pixels, so i and j run from -6 to 5 . The result is shown in Fig. 2.

4. Down-sample the image by an integer factor of k in each dimension. In this example we use $k = 4$ and the new image has dimensions 224 x 300. It is shown on the left side of Fig. 3.
5. Create a reference image by low-pass filtering the down-sampled image. The filter should be low-pass enough to remove those image elements usually characterized as mura. In this example we use a Gaussian filter with a scale of 2 deg. The result is shown on the right side of Figure 3.
6. We subtract the down-sampled test and reference images and convert to contrast by dividing by the mean of the two images.

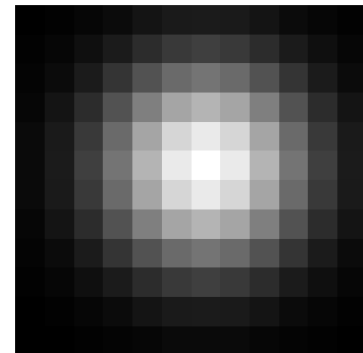


Fig. 2. A Gaussian kernel for pre-filtering.

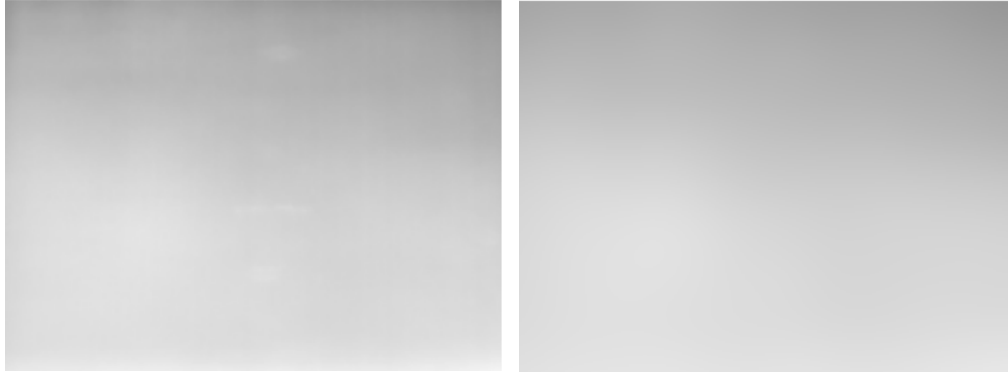


Fig. 3. Down-sampled test image (left). Reference image (right).

7. (Optional) Mura near borders may be masked by the border. This can be implemented through a border mask image. In this example it is defined as

$$B(i, j) = 1 - b_{\text{gain}} \exp \left[-\pi \left(\frac{k}{r b_{\text{scale}}} \min[(i-1), (j-1), (I-i), (J-j)] \right)^2 \right], \quad (2)$$

where I and J are image height and width in pixels, and b_{gain} and b_{scale} are parameters with values of 1 and 0.5 deg, respectively. The border mask image then multiplies the contrast difference image. This attenuates contrast near the borders. A picture of the example border mask image is shown in Fig. 4.

8. Create a contrast-sensitivity function (CSF) filter. In this example it is a difference of a hyperbolic secant functions of different scales, one with its argument raised to a power,

$$S_{\text{CSF}}(u) = g \left\{ \text{sech} \left[\left(\frac{u}{f_0} \right)^p \right] - a \text{sech} \left(\frac{u}{f_1} \right) \right\}, \quad (3)$$

where u is radial frequency in cycles/deg, and g, a, p, f_0 and f_1 are parameters. In this example we have used parameters $g = 373.083, f_0 = 4.1726, f_1 = 1.3625, a = 0.8493, p = 0.7786$. This filter is defined in the discrete-Fourier-transform (DFT) domain, and is conveniently constructed equal in size to the image, in which case

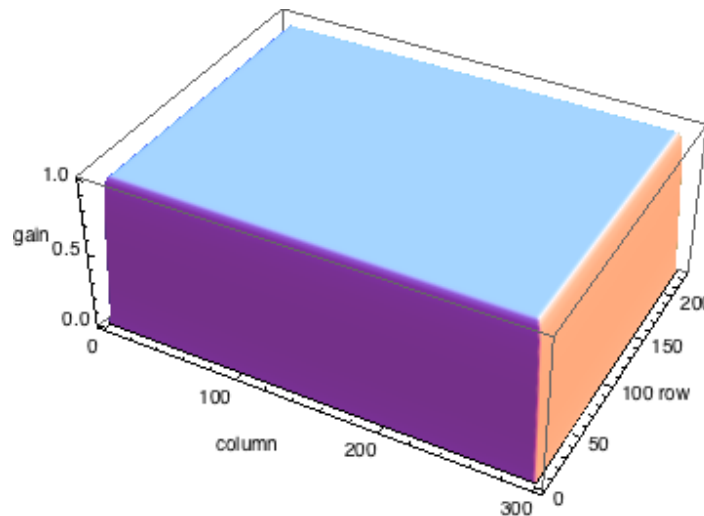


Fig. 4. Border mask image, shown as a 3D surface.



$$u = \frac{r}{k} \sqrt{\left(\frac{i}{w}\right)^2 + \left(\frac{j}{h}\right)^2}, \quad (4)$$

where i and j are column and row pixel indexes, and w and h are the width and height of the image in pixels, and r and k are as defined above. The CSF takes into account viewing distance, which determines the visual resolution r . Here we have assumed $r = 48$ px/deg, which assumes a viewing distance of 2750 screen pixels. Other values can be used for specific applications or by agreement. The value should be reported. The Fourier spectrum of this CSF filter is shown in Fig. 5.

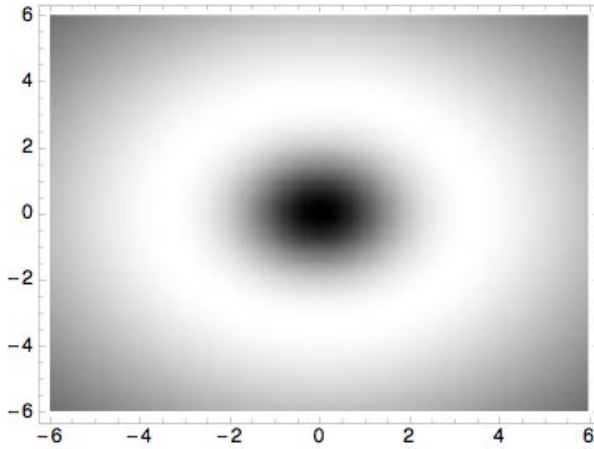


Fig. 5. Spectrum of the CSF filter. The axes are cycles/deg.

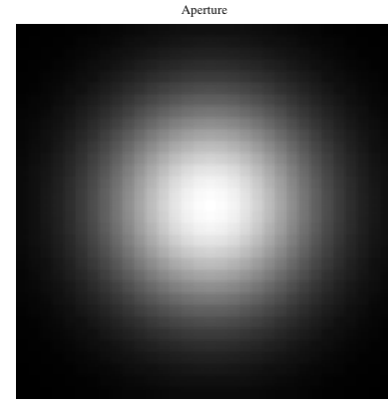


Fig. 6. Aperture function. This image is 2° wide.

9. The difference image is convolved with the CSF filter to produce the filtered difference image. If the filter is created in the DFT domain, as in the example above, the convolution is achieved through application of a DFT to the difference image, multiplication in the DFT domain, and an inverse DFT operation.
10. Construct an aperture function to represent the sensitivity surrounding the point of fixation. In this example we use a Gaussian with a scale of 1 deg. It is shown in Fig. 6.
11. Compute the JND image from the formula

$$J_{\text{mura}}(i, j) = \left[\left(\frac{k}{r} \right)^2 W(i, j) \otimes |F(i, j)|^\beta \right]^{1/\beta}, \quad (5)$$

where F is the filtered difference image, W is the aperture function, β is a parameter with a value of 2.4, and \otimes indicates convolution. An example of J_{mura} is shown in Fig. 7. The maximum is 1.7 JND. The bright regions indicate the locations of visible mura. Values greater than one are estimated to be visible. We also show a colored threshold version, a pseudo-colored version, and a 3D surface in Fig. 7. The JND image is a good indicator of where mura are in the image, and it is scaled in units of just noticeable difference (JND).

12. Compute the maximum $J_{\text{mura-max}}$. In this case it is 1.7.
13. Another summary measure that reflects the distribution of mura over the DUT is the total $J_{\text{mura-total}}$, computed as

$$J_{\text{mura-total}} = \left[\left(\frac{k}{r} \right)^2 \sum_x \sum_y J_{\text{mura}}^\psi(x, y) \right]^{1/\psi}, \quad (6)$$

where ψ is a parameter, which in this example is $\psi = 4$. The result for this example is $J_{\text{mura-total}} = 2.94$.

14. To analyze large scale non-uniformity, perform steps 1 through 8, without the aperture and scanning described in steps 9-11 and with an appropriate set of CSF parameters. This is called $J_{\text{mura-single}}$.



15. Color non-uniformities can optionally be measured by applying an appropriate CSF to chromaticity data and calculating the same defects.

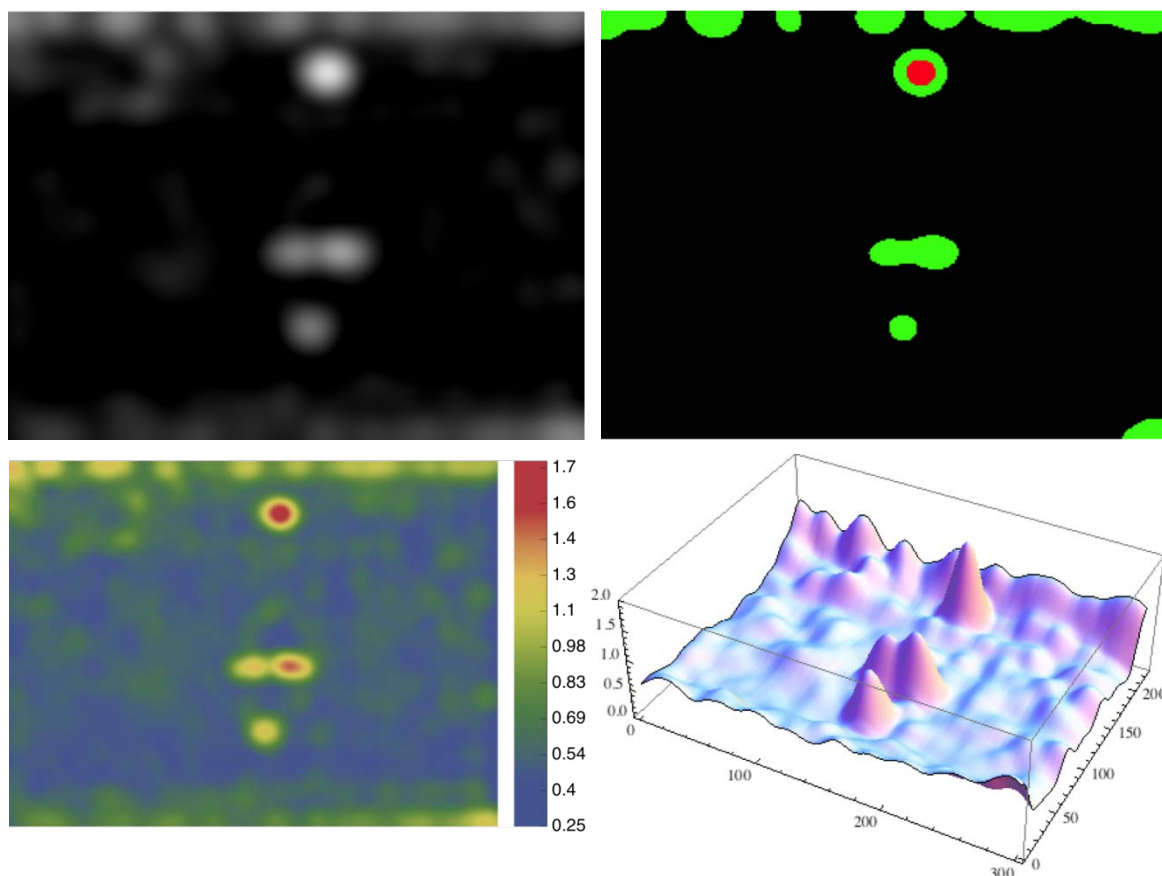


Fig. 7. JND images of the DUT. (a) JND image showing the range from 0.5 to 2. (b) Colored rendering of the JND image: green > 1, red > 1.5. (c) Pseudo-color rendering of the JND image. (d) JND image result as a surface plot.

REPORTING: Report the maximum JND, and total JND values calculated with and without an aperture function. If using a CSF that can be applied to color data, report the resulting JND values for the color data as well. Provide a low resolution map of JND for the image.

COMMENTS: (1) contrast-sensitivity function: The steps mentioned above require a high level of sophisticated image processing and therefore there could be large variations in the reported result depending on the exact methodology used. One possible method that can be applied to perform the above steps is the *Standard Spatial Observer* method developed by NASA. [Watson, A. B. (2006). *The Spatial Standard Observer: A human vision model for display inspection* SID Symposium Digest of Technical Papers, 37, 1312-1315. Watson, A. B. (2010). US Patent No. 7783130 B2.]

(2) Mura categorization: Once mura defects have been found, it is many times desirable to categorize them based in their size, shape, orientation, and intensity. Categorization is generally very dependent on the specific display technology used, and even how it is manufactured, so categorization will not be covered in this standard.

Reporting example (Sample data) Mura Analysis of Area Uniformity	
Screen Setting	White (100%)
$J_{mura, max}$	1.7
$J_{mura, single}$	3.5
$J_{mura, total}$	2.94
Max color JND	2.8
Single Color JND	3.3
Total Color JND	1.9
horizontal pixel pitch	1/48 deg
vertical pixel pitch	1/48 deg



8.4 DISPLAY SPARKLE

ALIAS: sparkling, random moiré

DESCRIPTION: *Sparkle* on display devices is an unwanted and disturbing visual effect caused by the interaction of a scattering anti-glare (AG) layer and the display subpixel matrix [1]. Display sparkle is perceived by the human observer as a random pattern of tiny spots across the display area that is rapidly changing its appearance with viewing direction. On a display screen which is showing one of the primary colors, the random sparkle pattern is constituted by dark spots, on a white display the sparkle granules show the individual primary colors that add up to white. Sparkle is visible from viewing distances from which the individual pixels of the display cannot be distinguished by the observer. The visual appearance of sparkle is similar to that of speckle, the latter one being an interference phenomenon occurring in coherent light only, while sparkle as described here appears in incoherent light.

Specularly reflecting particles are sometimes added to coatings, paints, and varnishes in order to intentionally produce a glittering effect which is also called sparkle [2]. For optimization of displays with respect to control of reflections of ambient light sources by scattering anti-glare layers, the level of sparkle has to be limited to low values by a series of iterated measurements, evaluations and AG-layer modifications.

The appearance of sparkle depends on the condition of observation as illustrated in Figure 1. At a viewing distance from which the human observer cannot resolve individual subpixels of a display, sparkle is seen as a random pattern of dark (or colored) spots on a brighter and uniform display background. At higher resolutions, as obtained with optical means, for example with macro-lenses in combination with imaging LMDs, pixels or subpixels can be distinguished, and sparkle manifests itself as a distortion of the pixel and subpixel areas and their contours (see right of Figure 1).

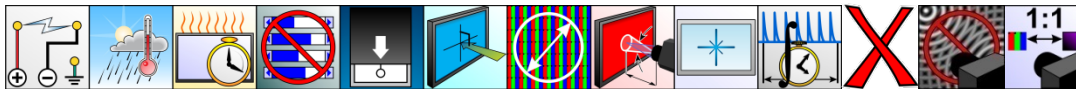
Measurement and evaluation of the sparkle level is usually based on a setup for imaging the combination of a display and an AG film which may be laminated onto the display (common in final products), or available as separate items (common in the R&D stage [3]). Imaging photometers, colorimeters or scientific-grade electronic cameras can be used for capturing and recording such electronic images under well-defined conditions. The LMD output should be proportional to the DUT luminance and the LMD spectral sensitivity should cover the visible wavelength range (380 nm - 780 nm). However, it does not have to reproduce the CIE photopic luminous efficiency function, $V(\lambda)$.

Symbol: s [1] **Units:** [1] dimensionless

See also: 18.6 VISUAL OBSERVATIONS

APPLICATION: Display sparkle is evoked by the combination of a display subpixel array and randomly structured surfaces, for example, scattering AG layers. Sparkle can occur for all emissive and transmissive direct-view display technologies (LCDs, organic and inorganic LED displays, etc.).

SETUP:



OTHER SETUP CONDITIONS: Display a uniform test pattern of one of the primary colors, preferably green. Allow the display luminance to stabilize. Align the display with respect to the imaging LMD with the optical axis of the LMD perpendicular to the display surface and in the center of the uniform test pattern. Align the display pixel matrix parallel to the array of detector elements (pixels) of the imaging LMD, e.g., by monitoring moiré interferences. Select the objective lens and working distance to sample one display pixel by more than 2x2 LMD pixels. Focus on the pixel matrix of the display under test. Avoid ambient light on the field of measurement. Set the aperture stop small enough to avoid excess (directional) averaging and wide enough to avoid diffraction. This may be realized for aperture angles of the LMD below 0.5° or even below 0.35° according to [4]. Set the exposure time of the imaging LMD to obtain the highest possible output level without over-exposure (clipping). Make sure that the detector array dark signal and lens vignetting (shading) are compensated for.

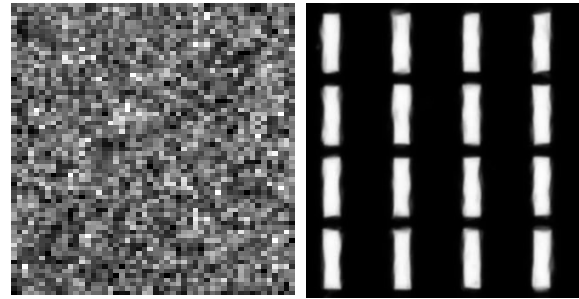


Fig. 1. Appearance of *sparkle* at low magnification (left) at which the individual pixels cannot be distinguished and at a high magnification as produced with an optical system (right). The bright rectangles are subpixels of the same primary color, the contours of which are distorted by the structures of the scattering AG layer.



PROCEDURE: Acquire an image (preferably the average from a series of images in order to improve the signal to noise-ratio) of the combination of a display and an AG-layer. Apply filtering to separate the random intensity modulations (sparkle) from the periodic modulations arising from the display pixel matrix.

The images on which the sparkle evaluation is based are given by arrays of luminance (or wavelength-weighted radiance) values, $L(x, y)$, obtained from the imaging LMD:

$$image := L(x, y); 0 \leq x \leq H; 0 \leq y \leq V; x, y \in \mathbb{N} \quad (1)$$

where H and V is the number of LMD detector pixels in the horizontal and vertical direction, respectively.

Evaluation of the sparkle level

Measurement and objective evaluation of sparkle levels is based on electronic images of the combination of display and AG-layer which are filtered either in the spatial or in the frequency domain. Spatial filtering may be achieved with a kernel of rational (fractional) dimensions (in terms of DUT image pixel pitch per LMD pixel pitch) in order to separate the periodic lateral modulations caused by the display pixel matrix from the statistic modulations that constitute the sparkle level. In the frequency domain, the components corresponding to the pixel matrix can be identified and suppressed according to established image processing methods and procedures [5].

After filtering, i.e. removal of the periodic modulation from the pixel matrix, the sparkle level is specified by the quotient of the standard deviation, σ , and the average intensity value, μ , of a suitable selected region of interest (ROI) within the filtered images. That quotient is also known as *speckle contrast*.

Spatial filtering

Spatial filtering is accomplished by changing the value of each pixel according to the intensities of the neighboring pixels. The number of adjacent pixels that are usually considered in image processing is the square of odd integers (e.g., 9, 25, etc.). Generally, without special adjustments during image acquisition, the image of one display pixel is sampled by a non-integer (i.e., rational, fractional) number of LMD detector pixels. In order to suppress periodic modulations caused by the display pixel matrix we apply spatial filtering with a kernel that is matched to the pixel dimensions of the DUT image, specified in terms of LMD pixels. The ratio of LMD pixel per DUT image pixel is also called *image sampling rate*, S_R . That sampling rate can be determined by counting the multitude of periods in a profile (see 7.2-5: Window width), by Fourier transformation of the profile (can be done in a spreadsheet) or by 2D Fourier transformation of the image.

The concept of a “rational kernel” for an image sampling rate of 3.5 is illustrated in Figure 2. Starting with a kernel with odd integer dimensions (core-kernel, here: 3x3, next odd integer $< S_R$), rational increments α ($0 \leq \alpha \leq 1$) are added at the periphery to form a square region that is identical to the square display pixel area. The intensity values within the integer 3x3 kernel are weighted with one, the vertically and horizontally surrounding values are weighted with α , the diagonal values with α^2 . If the sampling rate is 3.5 (i.e., number of LMD pixels per DUT image pixel, as illustrated in Figure 2), then $\alpha = (3.5 - 3)/2 = 0.25$.

The number of elements of the square kernel, k^2 , is given by the closest odd integer $> S_R$, which is 25 for $S_R = 3.5$. The sum of the weighted intensity levels of the image is divided by the sum of the weights and then assigned to the center pixel. The filtered image, L^* , thus becomes:

$$L^*(x, y) = L * K = \sum_{s=-a}^a \sum_{t=-a}^a K(s, t) \cdot L(x + s, y + t), \text{ where } a = (k - 1)/2 \quad (2)$$

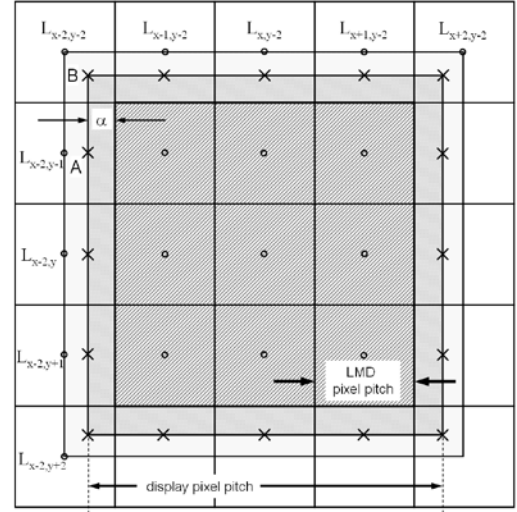


Fig. 2: A display pixel (gray square) in relation to the matrix of the imaging LMD detector elements (small squares).

$$\begin{bmatrix} \alpha^2 & \alpha & \alpha & \alpha & \alpha^2 \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha^2 & \alpha & \alpha & \alpha & \alpha^2 \end{bmatrix} \cdot \frac{1}{S_W}$$

$$S_W = (N - 2)^2 + 4(N - 2)\alpha + 4\alpha^2$$

Fig. 3: 5x5 filter kernel ($N=5$), $K(s, t)$, for the case illustrated in Figure 2, i.e. for sampling rates $S_R > 3$ [LMD pixels per display pixel].



The filter kernel shown in Figure 3 can be translated across the image in steps corresponding to the LMD pixel pitch [3] or the procedure can be modified with translation steps corresponding to the display pixel pitch [6]. Note, that when the center of the kernel is at the periphery of the image (outermost rows and columns) non-existing picture elements may be included in the filtering, producing distorted results. An edge region of width $(k - 1)/2$ image pixels should be excluded from evaluation of average and standard deviation.

The square 2D filter kernel according to Figure 3 can be separated into two 1D kernels that are applied one after the other in the horizontal and the vertical direction (or vice versa). In the one-dimensional case the convolution described here is equivalent to the *moving window averaging* operation as introduced in appendix B18 DIGITAL FILTERING BY MOVING-WINDOW AVERAGE. The algorithm described in B18 can be extended to rational (fractional) window dimensions as sketched in Figure 4. The average values μ_y for, e.g., a row, are obtained as:

$$\mu_y = \left[\alpha \cdot L_{x-p-1,y} + \sum_{j=-p}^p L_{x+j,y} + \alpha \cdot L_{x+p+1,y} \right] / (P + 2\alpha) \quad (3)$$

where P is the largest, odd number $< w$, $p = \text{floor}(P/2)$ and $\alpha = (w - P)/2$, and w the window width.

This moving averaging filter can be easily implemented in a spreadsheet software. Images, i.e., 2D arrays of luminance values, can be filtered by first filtering in one direction, e.g., row by row, then followed by filtering in the other direction, i.e., column by column.

ANALYSIS: Evaluate the sparkle level as the quotient of the standard deviation and mean value after filtering. Exclude the edge regions of the filtered image (a framing stripe of width $(k - 1)/2$ image pixels) from this evaluation. The cropped filtered image or a suitably selected ROI is $L^*(x', y')$.

The average value, μ , is calculated by summing up all intensity values of the cropped filtered image, $L^*(x', y')$, and dividing the sum by the number of summed image pixels, $H' \cdot V'$.

$$\mu = \sum_{x'} \sum_{y'} L^*(x', y') / (H' \cdot V') \quad (4)$$

With the average value, μ , the square of the standard deviation, σ^2 , becomes:

$$\sigma^2 = \sum_{x'} \sum_{y'} (L^*(x', y') - \mu)^2 / (H' \cdot V' - 1) \quad (5)$$

The sparkle level of the selected ROI or cropped image, s , is then given by the quotient of the standard deviation, σ , and the average value, μ :

$$s = \sigma / \mu \quad (6)$$

REPORTING: Report the sparkle level of the combination of display and AG-layer together with the imaging conditions (lens aperture setting, working distance) and the resulting *image sampling rate* (the number of LMD pixels per pixel of the display image) to make the measurement reproducible. It is useful to evaluate and specify the lowest possible sparkle level for each measurement setup which is given by the display without AG layer (NULL-test).

REFERENCES:

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- [3] M. E. Becker, J. Neumeier: "Optical Characterization of Scattering Anti-Glare Layers", Proc. SID2011
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- [6] J. Gollier, et al.: "Display Sparkle Measurement and Human Response", Proc. SID2013

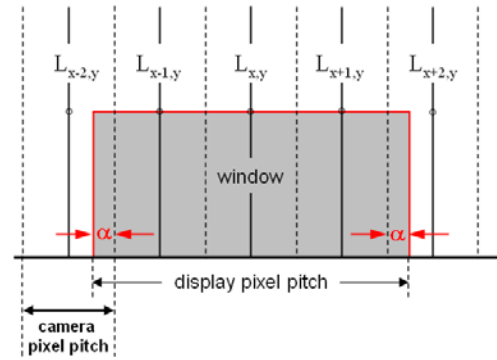


Fig.4: Averaging window of width $3+2\alpha$ LMD pixels in the 1D case.



9. VIEWING-ANGLE MEASUREMENTS

In this section, we consider the measurement of display characteristics as a function of viewing direction. The main objective is to assess viewing-direction related changes in the physical parameters, perceptual attributes, and overall image quality. The number of measured viewing directions could range from a few (two, four or eight directions) to many (several along the horizontal, vertical and oblique directions or in the whole angular viewing space), while the test patterns and data analysis depends on the applicable metric.

We often measure the luminance and the chromaticity coordinates of one or more full-screen colors, such as W, K, R, G, B, C, M, Y, or other color (R, G, B) or S gray shade patterns, for a given set of viewing directions in darkroom conditions. The CCT or others similar quantities like gray-scale inversion or relative color-gamut area can also be computed, and are described in the following sections.

These viewing-angle metrics are applicable to direct-view displays of any technology. For reflective displays, careful attention needs to be given to the ambient illumination environment, see Chapter 11 Reflection Metrics. Front-projector displays rely on a screen; separate considerations for screens are found in Chapter 16 Front-Projector-Screen Metrics.

PLEASE NOTE: Extensions of viewing-angle metrics:

- Non-Normal Design Viewing Direction:** All the following viewing-angle measurements specify that the reference direction is the normal to the display surface, the z -axis ($\theta = 0^\circ$). Some displays are designed for a viewing direction that is not along the normal. When agreed upon between all interested parties or when explicitly specified in the metric description, the design-viewing direction (θ_{vd} , ϕ_{vd}) may be used as the reference direction, and all measurements are made relative to that design-viewing direction instead of the normal.
- Box Pattern Measurements:** All the following viewing-angle measurements have been applied to full-screen patterns. Centered box patterns can be similarly measured, but all interested parties must agree and any reporting vehicle must clearly indicate that a box measurement has been made and not a full-screen measurement.
- Viewing-Angle Uniformity:** All viewing-direction related parameters that are described herein can also be evaluated at several locations on the display in order to assess for possible lateral variations. This is described in Chapter 8 Uniformity Metrics.
- Viewing-Angle Gray-Scale:** We can also do an analysis of the gray scale as a function of viewing angle as described in Chapter 6 Gray-Scale and Color-Scale Metrics.
- Colors:** A number of the following metrics refer to measuring black, white, or gray shades. In many cases the measurement may also be applied to full-screen colors as well.

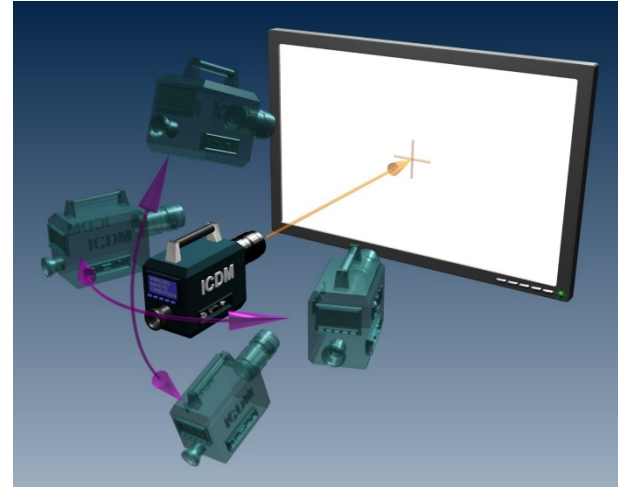
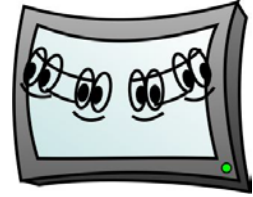
TYPES OF MEASUREMENT APPARATUS: Photometric (luminance, etc.), colorimetric, and spectrally-resolved data can all be obtained for viewing-angle measurements. In addition, the angularly resolved detail of the obtained data depends upon the apparatus you are using:

- Point-and-Shoot Detectors:** Here the detector is manually moved to the desired viewing-angle locations, and the data are recorded. It is usually very convenient to have the detector mounted on a goniometric device or to have the display mounted on a rotation platform to acquire the manual data. However, most viewing-direction related measurements involve a fairly large quantity of individual measurements and can benefit from some automation.
- Automated Goniometric Detectors:** Here the detector is moved and data recorded using an automated goniometer.
- Viewing-Field Array Detectors:** Here an array detector captures a very wide range of viewing angles all in one image through a suitable detector lens arrangement (See § B23 Conoscopic LMDs) or a projection type arrangement using a wide-angle lens. In both case the measurement device is placed close to the display (but not touching).

ANGULAR ACCURACY: Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure an accurate angular alignment ($\pm 1^\circ$ or less) between the LMD and the screen normal.

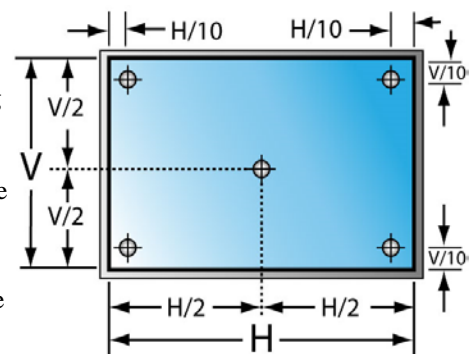
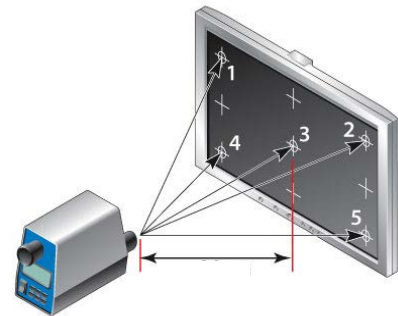
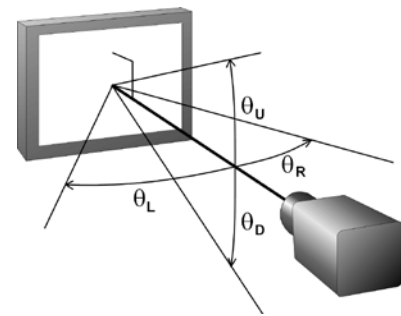
CATEGORIES OF DATA: There are several categories of data:

- Discrete-Angle Data:** The viewing-angle data are acquired at only a few discrete viewing directions, i.e., a few combinations of inclination angle θ and rotational angle ϕ , which angles have been defined in § 3.6.





2. **Profile Angular Data:** The viewing-angle data are acquired over a one-dimensional range of angles to resolve a profile of the data along a line (curved or straight), a certain direction, or other locus of points as a circle.
3. **Field or Map Angular Data:** A two-dimensional region of angles where viewing-angle information is captured for the entire region.
4. **Four-Point Viewing-Angle Data:** The viewing-angle data are acquired, with maximum angular increments of 5° , in four off-normal viewing directions ; sideways to the right $\theta_H = \theta_R$ ($\phi = 0^\circ$), upward $\theta_V = \theta_U$ ($\phi = 90^\circ$), sideways to the left $\theta_H = -\theta_L$ ($\phi = 180^\circ$), and downward $\theta_V = -\theta_D$ ($\phi = 270^\circ$).
5. **Generalized Viewing-Angle Data:** The viewing-angle data are acquired, with maximum angular increments of 5° , in eight off-normal viewing directions ; sideways to the right ($\phi = 0^\circ$), diagonally upward to the right ($\phi = 45^\circ$), upward ($\phi = 90^\circ$), diagonally upward to the left ($\phi = 135^\circ$), sideways to the left ($\phi = 180^\circ$), diagonally downward to the left ($\phi = 225^\circ$), downward ($\phi = 270^\circ$), and diagonally downward to the right ($\phi = 315^\circ$).
6. **Vantage-Point Viewing-Angle Data:** We typically measure five points, where the center point is number 3 and the corner points are 1, 2, 4, and 5, from upper left to bottom right. With a measurement distance of 30 cm from the center of the screen (location # 3), and the other measurement locations as defined in the next figure, the viewing directions for the measurements can be derived.
7. **Viewing-Field Polar Data:** The viewing-angle data are acquired with a maximum of five-degree intervals of inclination angle θ and a maximum of ten-degree intervals of rotational angle ϕ to create 360° polar plots identifying the behavior for any optical quantity of interest. The 360° polar plots (some call them radar plots) portray the hemisphere in front of the display in a two-dimensional graph. The distance from the center of the graph is the polar angle θ in spherical coordinates and the angle in the clockwise direction is the rotation angle ϕ from the x -axis in spherical coordinates. In order to properly convert goniometric or viewing angle coordinates to spherical coordinates, see Chapter 3 for the coordinate transformations.



DATA ANALYSIS AND REPORTING: There are several ways to analyze the acquired viewing-angle data:

1. **Threshold-Based Analysis:** The acquired viewing-angle data is analyzed in all measured viewing directions to determine the viewing-angle at which a specific threshold level criterion has been met, e.g. contrast-ratio ≥ 10 . The resulting threshold viewing-angles can be tabulated for all viewing directions with no more than three significant figures. Optionally, the threshold viewing-angles can be presented in a polar plot.
2. **Variation-Based Analysis:** The acquired viewing-angle data is analyzed to determine the change in optical characteristics in each measured viewing direction, relative to the characteristics measured in the normal viewing direction, e.g. luminance change ratio, and color variation. The off-normal variation in the measured optical characteristics can be presented in two-dimensional plots. Optionally, a threshold value can be included in these plots and the resulting threshold viewing-angles can be tabulated for each viewing direction.
3. **Criterion-Based Analysis:** The acquired viewing-angle data is analyzed to determine the number of occurrences a specific criterion has been met in each measured viewing direction, e.g. gray-scale inversions. The number of occurrences needs to be tabulated for each viewing direction.

DISCUSSION: (1) Optimum Viewing Directions: The optimum, or design viewing direction, is not necessarily limited to the horizontal and vertical planes but may be at any location in the viewing field, depending upon the technology and application. The polar representation obtained from the Viewing-Field Polar data can be valuable although it requires an extensive number of measurements. Alternately and for those cases, the Generalized Viewing-Angle data set can be used.

(2) Viewing angle versus viewing direction: As defined in § 3.6, a viewing direction is uniquely defined by two angles (θ , ϕ). As, in specifications sheets, viewing directions are most often limited to horizontal ($\phi = 0^\circ$ and 180°) and vertical planes ($\phi = 90^\circ$ and 270°), the definition of viewing direction is usually made through the sole incidence angle (θ) in those planes. By extension, viewing directions values are frequently referred to as being viewing angles. Additionally, the word “direction” is often used in a general sense (north, south, up, down, etc.), whereas “angle” often refers to an angular measure in degrees or radians.



9.1 FOUR-POINT VIEWING ANGLES

DESCRIPTION: We measure any optical quantity at the center of the screen and at four viewing angles relative to the perpendicular direction (two vertical angles, up and down ; and two horizontal angles, right and left) specified by the any company using a display in its own products or the display manufacturer. The resulting optical quantities can be compared with the manufacturer's specifications.

For example, manufacturers often describe the full-screen contrast ratios attainable at four angles about the screen. This is a procedure to confirm these claims. Instead of contrast ratios, the white luminance, black luminance, chromaticity coordinates, color difference metrics compared to a perpendicular measurement of the center screen, color temperature, etc., can all be evaluated at these four points and compared with corresponding manufacturing data.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full screen pattern of color $Q = W, K, R, G, B, S$, or other color as needed.

PROCEDURE:

1. Arrange the LMD to measure the desired optical quantity at screen center from the normal direction.
2. Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure an accurate angular alignment ($\pm 1^\circ$ or less) between the LMD and the screen normal for the four manufacturer defined off-normal viewing directions: upward $\theta_U = \theta_U$, downward $\theta_V = -\theta_D$, sideways to the right $\theta_H = \theta_R$, and sideways to the left $\theta_H = -\theta_L$.

ANALYSIS: For each of the four viewing directions perform any required calculations (as with contrast, color metrics, etc.)

REPORTING: Report the optical quantities measured and/or calculated. In the example we show a variety of measurements: luminance and chromaticity coordinates of full-screen white and black, color temperature, chromaticity coordinates and luminance of primary colors, and contrast.

COMMENTS: This measurement is often a verification of the manufacturer's specifications for the optical properties attainable at specified H&V viewing angles. The manufacturer must specify the angles and the value of the optical property to be measured at those angles.

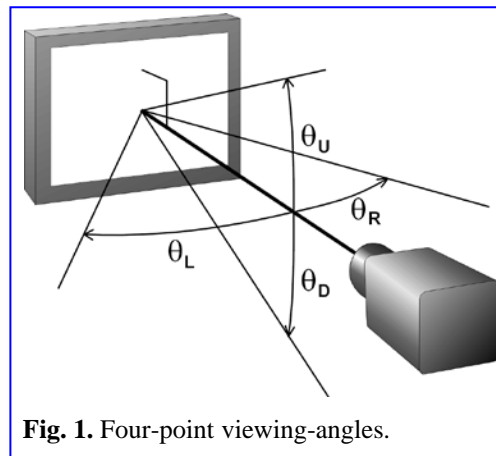


Fig. 1. Four-point viewing-angles.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting — Viewing Angle Sample Data

Direction	Angle	White				Black				
		L_W	X_W	Y_W	CCT	L_b	X_b	Y_b	C	
Up: θ_U	15°	85.6	0.298	0.322	7478	1.59	0.271	0.292	52.9	
Down: θ_D	10°	111	0.322	0.348	5967	3.79	0.269	0.285	29.2	
Right: θ_R	30°	39.4	0.323	0.346	5903	0.553	0.268	0.290	71.2	
Left: θ_L	30°	39.9	0.323	0.345	5920	0.609	0.270	0.297	65.4	
Direction	Angle	Red			Green			Blue		
		L_{red}	X_{red}	Y_{red}	L_{grn}	X_{grn}	Y_{grn}	L_{blu}	X_{blu}	Y_{blu}
Up: θ_U	15°	25.9	0.521	0.350	50.2	0.296	0.521	16.1	0.157	0.140
Down: θ_D	10°	35.4	0.520	0.349	63.5	0.305	0.518	20.3	0.166	0.165
Right: θ_R	30°	12.1	0.550	0.354	22.5	0.307	0.541	6.23	0.158	0.150
Left: θ_L	30°	12.3	0.548	0.353	22.7	0.306	0.540	6.34	0.158	0.150

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



9.2 THRESHOLD-BASED VIEWING ANGLES

DESCRIPTION: Measure the viewing angles up, down, left, and right that meet arbitrarily defined threshold levels of full-screen luminance, contrast ratio, and/or color variation.

Horizontal and vertical (H&V) angles are determined for viewing directions where luminance varies by 50 % of the perpendicular value, or any other agreed-upon threshold value. Viewing angles are determined for a threshold contrast ($C_T = L_W/L_K$) condition of 10:1 (optionally other threshold contrasts) using black-and-white full-screen center luminance measurements. Other contrasts may be specified to be the viewing angle where center full-screen contrast $C = L_W/L_K$ degrades by 50 % from its perpendicular (not necessarily the maximum) value. Similarly, the viewing angles associated with a change of black toward white by a small fraction of the white level, e.g., 5 % of L_W , could also be specified. H&V angles are determined for

viewing directions where color varies by $\Delta E = 5$ relative to the perpendicular value, or any other agreed-upon value of color shift. The viewing angle for the threshold condition is obtained from linear interpolation of contrast data as a function of angles with the angular increment no greater than 5° in each of the four directions, up, down, left, and right, relative to the screen perpendicular. **Units:** none, a ratio.

Symbol: C_T for viewing angle contrast threshold



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Full screen white and black patterns alternated (optionally primary colors).

PROCEDURE: Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure accurate angular alignments ($\pm 1^\circ$) between the luminance meter and the screen perpendicular. Incrementally increase the angles from the perpendicular with a maximum increment of 5° in off-normal viewing directions: upward θ_U , downward θ_D , right θ_R , and left θ_L . Make luminance measurements of full white and of full black at center screen with the luminance meter positioned at each of the off-normal H&V viewing angles. Optionally measure and record the CIE chromaticity coordinates of white, black, the full-screen primary colors, and/or the CCT of white.

ANALYSIS: For each white and black screen luminance measurement, compute the contrast ratio of white to black. Calculate the color difference values in $\Delta u'v'$ or ΔE units for each of the CIE (x,y) chromaticity coordinates measured on a full white screen using the perpendicular viewing direction as reference. Use linear interpolation to compute the four angular viewing directions upward θ_U , downward θ_D , right θ_R , and left θ_L that correspond to threshold levels of: (1) luminance, such as 50 % from its perpendicular value, (2) contrast ratio, such as $C_T = 10$ (or other values such as 20, 50, or as previously agreed upon), and (3) color difference such as $\Delta u'v' = 0.01$ or $\Delta E = 5$.

REPORTING: Report the viewing angles up, down, left, and right, for each threshold luminance, contrast ratio, and color difference to no more than three significant figures. Optionally, present plots of the computed contrast ratios, measured luminance values, chromaticity coordinates (or CCT) of white, and computed values of $\Delta u'v'$ or ΔE units along H&V axes.

COMMENTS: This measurement may be used to verify manufacturer's specifications for the contrast attainable at specified H&V viewing angles. The 50 % contrast degradation level is similar to the 3dB falloff used as a measuring point in electronics. The extreme maximum contrast of a display may not necessarily be determined by this measurement since the viewing directions are limited to those tilted vertically along the y-axis and tilted horizontally along the x-axis of the display. A more complete assessment of the display dependencies on viewing direction is obtained through other measurement in this chapter. Measurement of color differences of low-luminance black screens can be problematic due to limitations in sensitivity of some color meters (filter colorimeters, spectrometers, and spectroradiometers). The resulting long

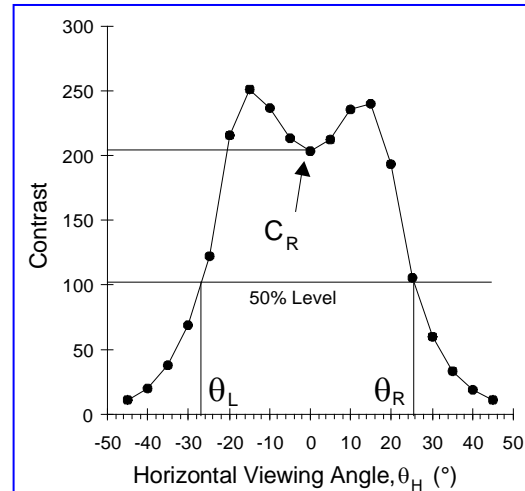


Fig. 1. Example of full-screen contrast ratio along the horizontal viewing angle.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting — Example		
Threshold Contrast Viewing Angles		
	$C_T = 100$	$C_T = 50$
Direction	Angle	Angle
Up: θ_U	11.2°	15.0°
Down: θ_D	3.81°	7.12°
Right: θ_R	25.3°	34.1°
Left: θ_L	27.1°	33.2°



integration times required to accurately measure such dark colors can render the measurement impractical for some.

9.3 GENERALIZED THRESHOLD BASED VIEWING ANGLES

DESCRIPTION: We measure the viewing angles at which thresholds in contrast reduction, luminance decrement, and/or color shift occur for eight azimuth angles $\phi = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ$ and 315° in increments of inclination angle of $\Delta\theta \leq 5^\circ$ from the normal to search for those threshold levels.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Full screen white and black patterns alternated (optionally primary colors). Thresholds of the quantities of interest must be specified.

PROCEDURE: Use a goniometric positioning device such as a rotating platter or discrete angle gauge blocks to assure accurate angular alignments ($\pm 1^\circ$) between the luminance meter and the screen perpendicular. Starting from the normal direction (perpendicular to the screen) incrementally increase the angles from the perpendicular with an increment of $\Delta\theta \leq 5^\circ$ in off-normal viewing directions for eight azimuth angles $\phi = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ$ and 315° . Make luminance measurements of full-screen white and of full-screen black at center screen with the luminance meter positioned at the normal and at each of the off-normal horizontal and vertical (H&V) viewing angles. Optionally measure and record the CIE chromaticity coordinates of white, black, the full-screen primary colors and/or the CCT of white at each position.

ANALYSIS: For each white and black screen luminance measurement, compute the contrast ratio of white to black. Calculate the color difference values in $\Delta u'v'$ or ΔE units for each of the CIE x,y chromaticity coordinates measured on a full white screen using the perpendicular viewing direction as reference. Use linear interpolation to compute the angular viewing directions that correspond to threshold levels selected. For example, (1) **luminance**, such as 50 % from its perpendicular value, (2) **contrast ratio**, such as $C_T = 10$ (or other values such as 20, 50, or a fractional decrease in contrast, or as previously agreed upon), (3) **color difference** such as $\Delta u'v' = 0.01$ or $\Delta E = 5$, or any other threshold metric that is of interest and is agreed upon by all interested parties.

REPORTING: Report the measured or interpolated viewing angles, for each threshold luminance, contrast ratio, and color difference to no more than three significant figures. Optionally, present plots of the computed contrast ratios, measured luminance values, chromaticity coordinates (or CCT) of white, and computed values of $\Delta u'v'$ or ΔE units along H&V axes. Directions can be labeled as Right, Up-Right, Up, Up-Left, Left, Down-Left, Down and Down-Right for $\phi = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ$ and 315° respectively.

COMMENTS: Compared to the threshold-based measurement method this generalized method is of best use when the viewing cone characteristics of the display are highly asymmetric or off-axis or if the user's point of interest is outside the usual horizontal and vertical directions.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting — Example		
Threshold Contrast Viewing Angles		
	$C_T = 100$	$C_T = 50$
Direction	Angle	Angle
Right	23.5°	27.2°
Up-Right	17.2°	22.4°
Up	11.2°	15.0°
Up-Left	17.5°	22.2°
Left	32.1°	33.2°
Down-Left	25.0°	27.3°
Down	3.81°	7.12°
Down-Right	22.1°	24.2°



9.4 VIEWING-ANGLE LUMINANCE CHANGE RATIO

ALIAS: Luminance degradation ratio

DESCRIPTION: We measure the relative change between the luminance at any measurement direction and the luminance at the reference viewing direction for a full-screen pattern at center screen. It is mainly intended to be used with a white or gray-shade patterns. **Units:** None, a ratio. **Symbol:**

$\Delta L/L_{Q,R}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen color Q pattern: white ($Q = W$), black ($Q = K$), or gray ($Q = S$, with $R = G = B$). (Here, the index Q is a variable that specifies the selected full-screen display color.)

PROCEDURE:

1. Apply the selected full-screen pattern of color Q .
2. Measure the luminance $L_Q(\theta, \phi)$ values at each selected measurement direction for full screen color Q to obtain the four-point viewing-angle data. Optionally the generalized viewing-angle data or viewing-field polar data can be obtained.
3. If not part of the selected measurement direction set, repeat this measurement at the reference viewing direction (θ_{vd}, ϕ_{vd}), which will typically be the normal direction (0, 0): $L_{Q,R} \equiv L_Q(\theta_{vd}, \phi_{vd})$.
4. Compute the luminance change ratio $\Delta L_Q(\theta, \phi)/L_{Q,R}$ for each measurement directions as follows:

ANALYSIS: Luminance change ratio $\Delta L_Q(\theta, \phi)/L_{Q,R}$ is expressed as follows for any measurement direction (θ, ϕ):

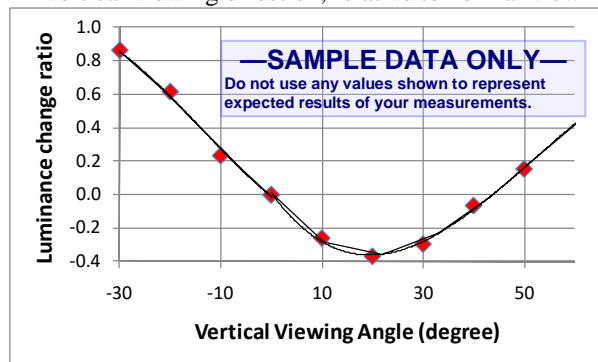
$$\frac{\Delta L}{L_R} \equiv \frac{\Delta L_Q(\theta, \phi)}{L_{Q,R}} = \frac{L_{Q,R} - L_Q(\theta, \phi)}{L_{Q,R}}. \quad (1)$$

Here, $L_R \equiv L_{Q,R} \equiv L_Q(\theta_{vd}, \phi_{vd})$, is the luminance of the full-screen pattern Q in the reference viewing direction.

REPORTING: The off-normal variation in the measured optical characteristics can be presented in two-dimensional plots. Optionally, a threshold value can be included in these plots. You should clearly state the reference viewing direction if not the normal direction (z -axis). If a threshold value for the luminance change ratio is of interest, then it should be reported along with the threshold level used; e.g., $L_{Q,R} \leq 0.50, 0.30$, or some other agreed-upon threshold. The resulting threshold viewing-angles can be tabulated for all viewing directions with no more than three significant figures.

COMMENTS: (1) **Colors:** Whereas this measurement normally employs white, black, or gray-shade full-screen patterns, it can also be applied to full-screen colors as agreed upon by all interested parties.

DATA EXAMPLE: Example of the luminance change ratio $\Delta L/L_{S=200,R}$, in the vertical viewing direction, relative to normal viewing direction.



— SAMPLE DATA ONLY —

Do not use any values shown to represent expected results of your measurements

Analysis and Reporting
Viewing-angle color variation

$\Delta L/L_{S=200,R} = 0.40$

Direction	Angle
Up: θ_U	54°
Down: θ_D	14°
Right: θ_R	64°
Left: θ_L	62°



9.5 VIEWING-ANGLE PERCEPTUAL METRIC

DESCRIPTION: This metric uses the procedures of § 9.4 Viewing-Angle Luminance Change Ratio - and § 9.6 Viewing-Angle Color Variation to determine the relative change in image quality as a function of viewing direction. It is based on perceptual studies and provides a criteria which best adapted for the evaluation of television displays. **Units:** None. **Symbol:** ΔQ_I .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen pattern with gray-shade $S = R = G = B = 200$, for eight bit signals.

PROCEDURE: Apply the required full-screen gray-shade pattern $S = R = G = B = 200$, for eight-bit signals. Measure the luminance L and (u', v') color coordinates at each selected measurement direction (θ, ϕ) to obtain the four-point viewing-angle data. Optionally the generalized viewing-angle data or viewing-field polar data can be obtained. If not part of the selected measurement direction set, repeat this measurement at the normal direction $(0,0)$ for u'_0 , v'_0 , and L_0 . Compute the luminance change ratio $\Delta L(\theta, \phi)/L_0$ for each measurement direction according to § 9.4, with $Q=S=200$. Compute the color variation $\Delta u'v'(\theta, \phi)$ for each measurement direction according to § 9.6, with $Q=S=200$. Compute $\Delta Q_I(\theta, \phi)$.

ANALYSIS: Image quality variation ΔQ_I is expressed as follows for measurement direction (θ, ϕ) :

$$\Delta Q_I = 5.13 \Delta L(\theta, \phi)/L_0 + 144 \Delta u'v'(\theta, \phi). \quad (1)$$

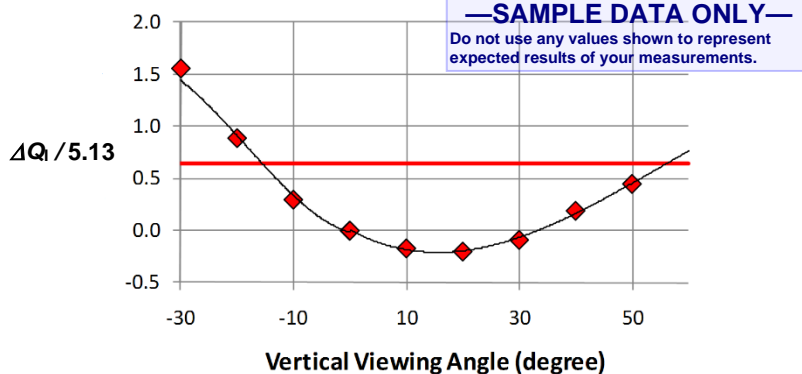
A relative change in image quality variation ΔQ_I of 3.3 is found to be acceptable in order to maintain an acceptable quality for television applications. This leads to the following equation to determine the threshold viewing direction:

$$\Delta L(\theta, \phi)/L_0 + 28 \Delta u'v'(\theta, \phi) \leq 0.64. \quad (2)$$

REPORTING: Present the interpolated viewing angles, in all four viewing directions, in tabular format. Reporting is made according to the general instructions, described in the introduction of this chapter. Optionally, the calculation results can be presented as a function of the horizontal and vertical viewing directions (see example below). You should clearly state the reference viewing direction for the calculation of $\Delta L/L_0$ and $\Delta u'v'$ if it is not on-axis in the normal direction.

COMMENTS: It must be noticed that the proposed weighting factors for luminance change ratio and color variation, with the corresponding threshold value is determined for television applications (See e.g., C. Teunissen, "Flat Panel Display Characterization: A Perceptual Approach", PhD Thesis, Delft University of Technology, Delft, the Netherlands, ISBN: 978-90-74445-86-3). For other display applications, other weighting coefficient for luminance change ratio and color variation and a different limit on the variation in perceived image quality may be applicable.

DATA EXAMPLE: Example of the perceptual metric results, according to Eq. (2), to determine, via interpolation, the threshold viewing angles in the vertical viewing direction.



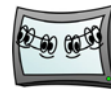
- SAMPLE DATA ONLY -

Do not use any values shown to represent expected results of your measurements

Analysis and Reporting
Perceptual Viewing Angles for

$$\Delta Q_I < 3.3$$

Direction	Angle
Up: θ_U	55°
Down: θ_D	16°
Right: θ_R	64°
Left: θ_L	62°



9.6 VIEWING-ANGLE COLOR VARIATION

ALIAS: viewing-angle color change

DESCRIPTION: Many color coordinates definitions have been standardized and can be used to define the color variation with respect to the measurement direction. They all require the measurements of X , Y and Z tristimulus values. **Units:** None.

Symbol: $\Delta u'v'_Q$.

It is here advised to use the (u', v') chromaticity coordinates system and to express the color variation as a distance $\Delta u'v'$ with respect to values observed at the reference viewing direction (the normal, the on-axis z -direction unless otherwise specified).

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen W or S achromatic display pattern. Although it is mainly intended for full white or grey shades patterns, this metric can also be applied to any other full-screen pattern as needed.

PROCEDURE:

- 1 Apply the selected W or S (below referred as Q) full-screen pattern.
- 2 Measure the X , Y and Z tristimulus values or (x, y) or (u', v') color coordinates at each selected measurement direction (θ, ϕ) to obtain the four-point viewing-angle data. Optionally the generalized viewing-angle data or viewing-field polar data can be obtained.
- 3 If not part of the selected measurement direction set, repeat this measurement at the reference viewing direction for u'_{Qref} and v'_{Qref} . If the reference direction is normal to the screen (along the z -axis) then $u'_{Qref} = u'_{Qref}(0, 0)$ and $v'_{Qref} = v'_{Qref}(0, 0)$, otherwise $u'_{Qref} = u'_{Qref}(\theta_{ref}, \phi_{ref})$ and $v'_{Qref} = v'_{Qref}(\theta_{ref}, \phi_{ref})$.
- 4 If needed compute $u'_Q(\theta, \phi)$ and $v'_Q(\theta, \phi)$ for each measurement directions
- 5 Compute $\Delta u'v'_Q(\theta, \phi)$.

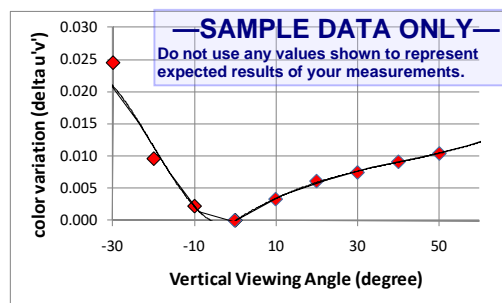
ANALYSIS: Color variation is expressed as follows:

$$\Delta u'v'_Q = \sqrt{[u'_Q(\theta, \phi) - u'_{Qref}]^2 + [v'_Q(\theta, \phi) - v'_{Qref}]^2} \quad (1)$$

REPORTING: The off-normal variation in the measured optical characteristics can be presented in two-dimensional plots. Optionally, a threshold value can be included in these plots. You should clearly state the reference viewing direction if not the normal direction (z -axis). If a threshold value for the color variation is of interest, then it should be reported along with the threshold level used; e.g., $\Delta u'v'_Q(\theta, \phi) \leq 0.010, 0.015, 0.020$, or some other agreed-upon threshold. The resulting threshold viewing-angles can be tabulated for all viewing directions with no more than three significant figures.

COMMENTS: It must be noticed that the proposed thresholds are larger than what is referred to for the evaluating color change visibility in a scene (like for uniformity measurements), which is close to 0.004. Indeed, in the case of viewing direction measurements or human evaluation the sampled and reference values cannot be observed at the same time.

DATA EXAMPLE: LEFT - Example of the color variation $\Delta u'v'_{S=200}$, in the vertical viewing direction, relative to normal viewing direction. RIGHT - Angles for a color change of $\Delta u'v'_{Q=W} = 0.005$.



- SAMPLE DATA ONLY -
Do not use any values shown to represent expected results of your measurements

Analysis and Reporting
Viewing-angle color variation
 $\Delta u'v'_{S=200} = 0.010$

Direction	Angle
Up: θ_U	50°
Down: θ_D	20°
Right: θ_R	64°
Left: θ_L	62°



9.7 GRAY-SCALE INVERSION

ALIAS: viewing-angle gray-scale inversion, gray-shade inversion, gray-level inversion

DESCRIPTION: We measure gray-shade or gray-scale inversion that occurs when for a given measurement direction, the gray scale of a display happens to be non-monotonically increasing. For example, it can happen at certain positions in the viewing field that for an increasing gray level a decrease of luminance is observed for a certain range of gray levels. This should not be confused with what some call a contrast inversion phenomenon when $C < 1$ because of the rendering of the black shade being brighter than the white shade, although the two may co-exist.

The amount of grey scale inversion can easily be evaluated at any measurement direction (θ, ϕ) by measuring the gray scale or EOTF (electro optical transfer function) of the display. The more grey shades patterns, the more accurate the derived value of gray-scale inversion parameter will be. In the following discussion the gray level, or just level, is describing the command which is used on each color channel to achieve a given full-screen gray-shade pattern. **Units:** None. **Symbol:** $G_{SI,M}$.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use full-screen gray-shade patterns.

PROCEDURE: For M gray levels $V_i, i = 1, 2, \dots, M$ selected out of a set of N total levels, we make viewing angle measurements for each resulting full-screen gray-shade pattern. For an eight-bit display, $V_1 = 0$ and $V_M = 255$. We would generally select $M = 9, 17, 33$, or 65 . (If needed, see appendix A12 Images and Patterns for Procedures for details on gray-level selection). A larger number of gray levels is desirable. However, selecting too many gray levels may introduce noise problems where the gray shades don't change their luminance rapidly enough with level change as may happen at either end of the gray scale, and false positives in establishing gray-scale inversions may result. 17 to 33 levels are considered adequate for general purpose displays. The measurement can proceed in two ways: (1) Each gray level V_i produces a full-screen gray shade L_i that is measured for all angular position of interest (θ, ϕ) , or (2) at each angular position (θ, ϕ) the gray levels V_i are cycled through obtaining the set $L_i(\theta, \phi)$ for $i = 1, 2, \dots, M$. In either case a full database of measurements of the gray-shade luminance for each selected level at each angle is produced, $L_i(\theta, \phi)$. In order to make clear how many levels M were used for the measurement, final quantity of interest $G_{SI,M}$ is referenced with this figure.

ANALYSIS: The gray-scale inversion value is calculated according to the following procedure for each angle of interest (θ, ϕ) . We first convert the luminance data to lightness data, and then at each angle we search through the lightness profile for inversions where the correct monotonicity of the profile is not preserved. For each measured angle (θ, ϕ) :

1. Reorder the data for each angular position (θ, ϕ) in order to have $j = 1$ representing the black state (minimum luminance) and $j = M$ representing the white state (maximum luminance) of the display.
2. Convert the luminance data $L_i(\theta, \phi)$ for $i = 1, 2, \dots, M$ to lightness $L_i^*(\theta, \phi)$ where the luminance $L_M(\theta, \phi)$ is used for white (see the appendix for a discussion of lightness if necessary: B1 Radiometry, Photometry, and Colorimetry):

$$L_i^*(\theta, \phi) = \begin{cases} 116 \left[\frac{L_i(\theta, \phi)}{L_M(\theta, \phi)} \right]^{1/3} - 16 & \text{for } \left[\frac{L_i(\theta, \phi)}{L_M(\theta, \phi)} \right] > \left(\frac{6}{29} \right)^3 \\ \frac{29^3}{3^3} \frac{L_i(\theta, \phi)}{L_M(\theta, \phi)} & \text{otherwise} \end{cases}$$

3. Calculate a monotonicity metric: $G_{SI}(j; \theta, \phi) = L_{j-1}^*(\theta, \phi) - L_j^*(\theta, \phi)$, for $j = 2, \dots, M$. If any $G_{SI}(j; \theta, \phi) > 0$ we have an inversion.
4. Calculate the maximum of the resulting set: $G_{SI\max} = \max[G_{SI}(2; \theta, \phi), G_{SI}(3; \theta, \phi), \dots, G_{SI}(M; \theta, \phi)]$.
5. The worst case inversion is given by:

$$G_{SI,M}(\theta, \phi) = \begin{cases} G_{SI\max}, & \text{if } G_{SI\max} > 0 \\ 0, & \text{if } G_{SI\max} < 0 \end{cases},$$

which is zero if there is no inversion observed.



In order to make things more clear for the casual programmer, this calculation method can easily be translated in the below pseudo-code where we are looking for the largest inversion:

```

For each angular position
  GSI = 0
  LstarMin = Lstar(1) %A large number, the white L* should be OK
  For Each i (From 2 to M)
    If Lstar(i) > LstarMin Then
      LstarMin = Lstar(i)
    Else
      If (LstarMin-Lstar(i)) > GSI Then
        GSI = LstarMin-Lstar(i)
      End
    End
  End
Next
Next

```

REPORTING: Report the occurrence (or not) of gray scale inversion, $G_{SLM}(\theta, \phi)$, at the selected viewing directions (θ, ϕ) ; determine the incidence angles in horizontal or vertical azimuthal planes at which gray scale inversion may occur; or report a polar contour line plot presenting the limit of gray scale inversion in the full viewing field as in Fig. 1.

COMMENTS: (1) Gray-Scale Inversion strength: Although no gray-scale inversion can usually be tolerated, there might be situations where some must be. The above metric can be used to determine in which measurement direction field or incidence angle range that is the case. Moreover, it can be used to evaluate the strength of gray-scale inversion when it occurs.

(2) Reasons to choose lightness to express it: Lightness is a metric that is more adapted than luminance to evaluate gray shades. In the case of the evaluation of inversion, one must consider that a displayed scene which is exhibiting gray shades and is observed at a given viewing direction or measured at this direction may include at the same time white and grey areas. Reference luminance is then logically chosen in these conditions to be the luminance of the white.

(3) Links to Gamma Distortion measurements: The measurement items that are needed for gamma distortion is very similar to those needed for gray scale inversion analysis. The two metrics may be evaluated from the same data set.

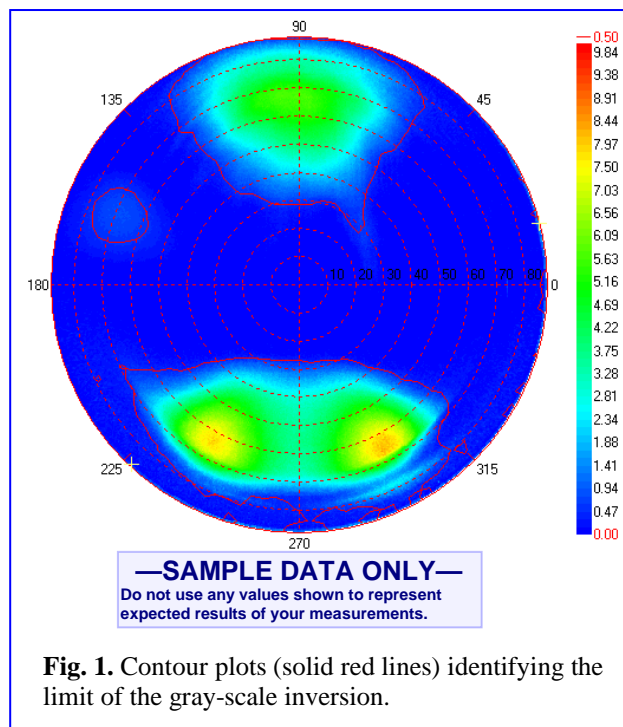


Fig. 1. Contour plots (solid red lines) identifying the limit of the gray-scale inversion.



9.8 VIEWING-ANGLE RELATIVE COLOR GAMUT AREA

ALIAS: color triangle area

DESCRIPTION: We measure the color gamut and color-gamut area of the primary colors as a function of viewing angle. The color gamut area is usually expressed by computing the area of the then defined triangle in a given color space. It is here advised to use the (u', v') 1976 CIE chromaticity coordinates system. The computed area can then be compared to various related quantities such as the area defined by popular color systems, or the total area delimited by the monochromatic colors locus. **Units:** None. **Symbol:** A_{RCG}

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use full-screen R, G and B display pattern. A measurement with a W full-screen display pattern can be added to enable measurement of the white location at the same time.

PROCEDURE:

1. Apply the first full-screen pattern (R, G or B)
2. Measure the X , Y & Z tristimulus values or (X, y) or (u', v') color coordinates at each selected measurement direction (θ, ϕ) ; these can be discrete or continuous positions depending upon the set of selected measurement directions.
3. Apply the second full-screen pattern (G, B or R) and repeat step 2
4. Apply the third full-screen pattern (B, R or G) and repeat step 2
5. Optionally apply the full-screen W pattern and repeat step 2

ANALYSIS: Compute the corresponding (u', v') color coordinates for each primary color at each viewing angle (θ, ϕ) . The relative area A_{RCG} in the (u', v') color diagram at each angle (θ, ϕ) is given by

$$A_{RCG}(\theta, \phi) = \frac{100\%}{2A_{u'v'}} \left| \det \begin{pmatrix} u'_G - u'_B & u'_R - u'_B \\ v'_G - v'_B & v'_R - v'_B \end{pmatrix} \right|_{(\theta, \phi)} \quad (1)$$

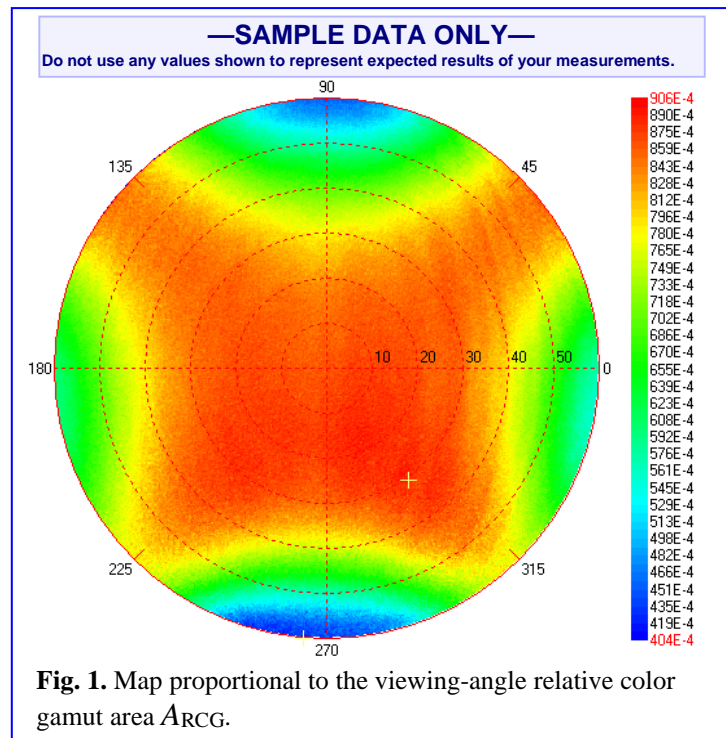
$$= (256.1\%) \left| (u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B) \right|_{(\theta, \phi)}$$

Here, $A_{u'v'} = 0.1952$ is the area of the spectrum locus and purple line in the (u', v') diagram.

Important Note: Without the absolute value the area becomes a signed surface that may be employed to investigate color inversions—see $S_{RCG}(\theta, \phi)$ in the next section, § 9.9)

REPORTING: You might report A_{RCG} at selected viewing directions versus incidence angle (θ, ϕ) in a 3D plot of the discrete angles, as contour lines, or as a two-dimensional plot of the full viewing field as shown in Fig. 1.

COMMENTS: Please see § 5.18 Gamut Area and § 5.18.1 Relative Gamut Area for more details on this type of measurement.





9.9 VIEWING-ANGLE COLOR INVERSION

DESCRIPTION: Detecting the measurement directions at which color inversion occurs can be based on the previously described color gamut area measurement. Indeed, the defined $A_{RCG}(\theta, \phi)$ metric is signed quantity that can be used to indicate a color inversion situation when negative. **Units:** None. **Symbol:** None

APPLICATION: See General Measurement Description for details.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use full-screen R, G and B display pattern.

PROCEDURE: Apply the measurement procedure as described in the previous method, § 9.8 Viewing-Angle Relative Color Gamut Area.

ANALYSIS: $S_{RCG}(\theta, \phi)$ is computed as below (it is A_{RCG} without the absolute value taken):

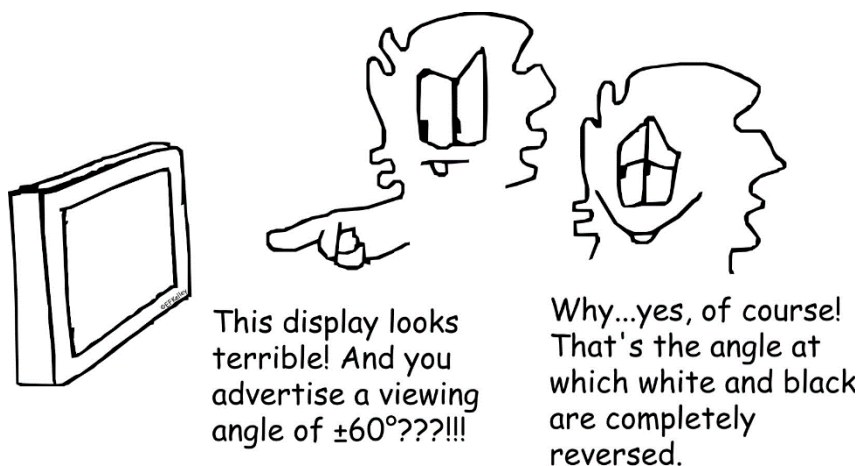
$$S_{RCG}(\theta, \phi) = \frac{100\%}{2A_{u'v'}} \det \begin{pmatrix} u'_G - u'_B & u'_R - u'_B \\ v'_G - v'_B & v'_R - v'_B \end{pmatrix}_{(\theta, \phi)} \quad (1)$$

$$= (256.1\%) [(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)]_{(\theta, \phi)}$$

Here, $A_{u'v'} = 0.1952$ is the area of the spectrum locus and purple line in the (u', v') diagram. If $S_{RCG}(\theta, \phi)$ changes sign it is an indication of a color inversion.

REPORTING: You should report if a color inversion is occurring at any selected viewing direction (θ, ϕ) . Similar plots can be made as in the last measurement method.

COMMENTS: None





9.10 VIEWING-ANGLE CCT

DESCRIPTION: Measure the correlated color temperature of a white or gray shade full-screen pattern as function of a set of viewing-angle directions. **Units:** K. **Symbol:** CCT.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use a full-screen W or S ($R = G = B$) display pattern.

PROCEDURE: For a specified set of viewing angles and full-screen white or gray pattern, measure the tristimulus values or chromaticity coordinates of the center screen at all selected angles (θ, ϕ).

ANALYSIS: CCT is computed according to (see § 5.19, and the appendix B1.2.1 for more details):

$$T(\theta, \phi) = 437 n^3 + 3601 n^2 + 6861 n + 5514, \quad (1)$$

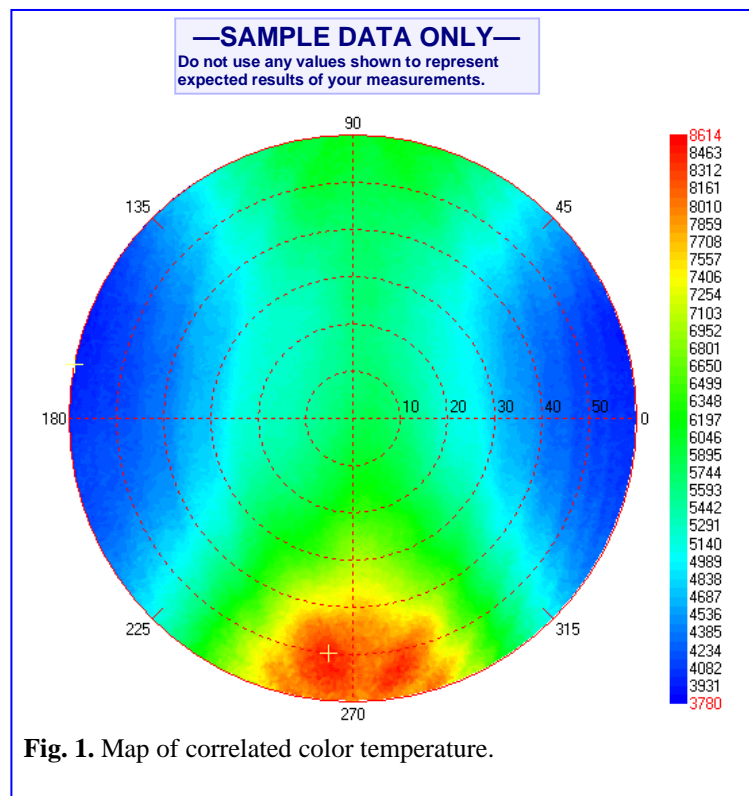
where

$$n = (x_w - 0.3320)/(0.1858 - y_w), \quad (2)$$

and where x_w and y_w are the (x, y) color coordinates of the sampled angular position.

REPORTING: Color Correlated Temperature can be reported in tabular form (See § 9.1 on 4 point measurements) angular cross sections (See § 9.2 on threshold) or polar plots as shown as an example.

COMMENTS: This metric is usually used in order to check for a certain white point color temperature. It is mainly meaningful for white or gray shades and should be avoided for any other (R, G, B or any other colored pattern).





9.11 LUMINOUS FLUX

ALIAS: light output, white light output

DESCRIPTION: Determine the luminous flux based upon sampling the illuminance from a white full screen at a number of angles in front of the screen. (The method is a goniometric illuminance measurement converted to

luminous flux.) **Units:** lm. **Symbol.** Φ .

APPLICATION: Emissive displays: This method is not suitable for front-projector displays; a special method is provided for front-projection displays, see Chapter 17 for more details.

SETUP: Prepare to measure the illuminance from a white full screen as a function of angle from and around the normal with the use of a cosine-corrected illuminance meter at a fixed radius r from the center of the screen. If practical, the radius should be at least ten times as large as the largest of the horizontal size (H) or vertical size (V) of the screen: $r \geq 10 \max(H, V)$. Because this is likely impractical for most facilities, we include an Estimated Luminous Flux in § 5.13.1 below.

Note: The illuminance meter measurement at each position must *not* be corrupted by reflections off of parts of the apparatus including the any bezel, mount, or holder for the screen, the positioning apparatus, or reflections from the walls or other items in the room—even reflections from items behind the display must be controlled.

As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a full-screen white pattern (e.g., FW_####x####.PNG). Note that the setup conditions require that the display be adjusted for useful operation as would be judged by trained observers.

PROCEDURE:

Determination of Angles of Measurements: Define n inclination angles θ_i from the normal for $i = 0, 1, 2, \dots, n$; see the figure. Let the normal be $\theta_0 = 0^\circ$ for $i = 0$. The θ_i need not be equally spaced between 0° and 90° . For each angle θ_i a number m_i of measurements will be made at equally-spaced angles $\phi_{ij} = j \, 2\pi^\circ/m_i$ for $j = 0, 1, 2, \dots, m_i - 1$ with respect to the x-axis in the counterclockwise direction. Here we define at the normal position $m_0 = 1$ (with only $j = 0$) and $\phi_{00} = 0$. Note that the ϕ_{ij} are equally spaced angles around the complete circle in this formalism, whereas the θ_i need not be equally spaced. Further, the m need not be the same for each annular ring identified by θ_i . The increment in ϕ is therefore $\Delta\phi = 2\pi/m_i$.

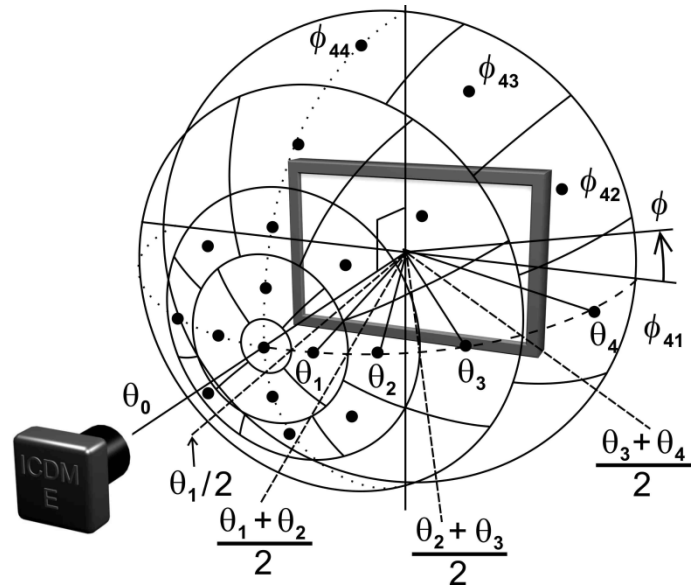
Illuminance Measurements: Measure the illuminance $E_{ij} = E(\theta_i, \phi_{ij})$ from the screen at each location (θ_i, ϕ_{ij}) using a cosine-corrected illuminance meter at a single radius r , where we suggest that $r \geq 10 \max(H, V)$.

Calculation: Calculate the flux based upon the analysis below.

ANALYSIS: For each inclination angle θ_i for $i > 0$ we associate an annular ring on the surface of the hemisphere. At the perpendicular position where $\theta_0 = 0$, we have a spherical cap. The luminous flux (in lumens, lm) will be given by

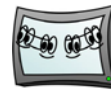
$$\Phi = r^2 \sum_{i=0}^n \sum_{j=0}^{m_i-1} E_{ij}(\theta_i, \phi_{ij}) \Omega_{ij}. \quad (1)$$

where Ω_{ij} is the solid angle associated with the each equal increment in ϕ ($\Delta\phi = 2\pi/m_i$ with $\Delta\phi = 2\pi$ for $i = 0$ and $m_0 = 1$) confined between the angles halfway between the selected (not necessarily equally spaced) θ_i :



VIEWING ANGLE

VIEWING ANGLE



$$\Omega_{ij} = \begin{cases} 2\pi \left[1 - \cos\left(\frac{\theta_1}{2}\right) \right], & \text{for } \theta_0 = 0 \text{ (the cap, } i = 0), \\ \frac{2\pi}{m_i} \left[\cos\left(\frac{\theta_{i-1} + \theta_i}{2}\right) - \cos\left(\frac{\theta_i + \theta_{i+1}}{2}\right) \right], & \text{for } 0 < i < n, \text{ for each } j, \\ \frac{2\pi}{m_n} \cos\left(\frac{\theta_{n-1} + \theta_n}{2}\right), & \text{for } i = n, \text{ for each } j. \end{cases} \quad (2)$$

Taking advantage of the fact that all the ϕ increments are equal allows us to write the luminous flux as

$$\Phi = r^2 \sum_{i=0}^n E_i(\theta_i) \Omega_i, \quad (3)$$

where

$$E_i = \sum_{j=0}^{m_i-1} E_{ij}(\theta_i, \phi_{ij}) \quad (4)$$

is the sum of the illuminance contributions around each annulus (E_0 is the luminance at the location of the cap at $\theta_0 = 0$), and where the solid angle of each annulus Ω_i is given by

$$\Omega_i = \begin{cases} 2\pi \left[1 - \cos\left(\frac{\theta_1}{2}\right) \right], & \text{for } \theta_0 = 0 \text{ (the cap, } i = 0), \\ 2\pi \left[\cos\left(\frac{\theta_{i-1} + \theta_i}{2}\right) - \cos\left(\frac{\theta_i + \theta_{i+1}}{2}\right) \right], & \text{for } 0 < i < n, \\ 2\pi \cos\left(\frac{\theta_{n-1} + \theta_n}{2}\right), & \text{for } i = n. \end{cases} \quad (5)$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Reporting Example		
Luminous Flux, Φ	1570	lm

REPORTING: Report the luminous flux Φ to no more than three significant figures.

COMMENTS: (1) **Display Size and Required Radius:** We stipulate a rather large radius for the illuminance meter from the center screen in order to reasonably minimize the errors that arise from the finite size of the screen. Different distances to different parts of the screen cause such errors. (2) **Sampling Sphere:** If such a large goniometric radius cannot be achieved, then a sampling sphere calibrated for flux measurements might be employed where its measurement port is moved about the screen and an average flux is calculated from a nine-point or 25-point sampling. (3) **Luminance Measurements:** The next subsection provides a method to approximate the flux when neither of the above two options are available.

9.11.1 ESTIMATED LUMINOUS FLUX

NOTE: This measurement method is based upon luminance measurements at the center of the screen. The estimated luminous flux obtained can be subject to uncertainties because of screen nonuniformities. However, a number of people have asked that this kind of estimation be included because of the ease with which the estimation can be made and an illuminance meter at a long distance from the screen is not required as in the parent method above. The method is carried out similarly to the above parent method only the center luminance is measured (at any reasonable radius) instead of illuminance.

MODIFIED PROCEDURE: The illuminance at angle (θ, ϕ_{ij}) is estimated by measuring the luminance $L_{ij}(\theta, \phi_{ij})$ at the screen center from that angle: $E_{ij} = E(\theta, \phi_{ij}) = L_{ij}(\theta, \phi_{ij}) (A/r^2) \cos \theta_i$, where the r^2 term ultimately cancels in the final calculation of flux:

$$\Phi = \sum_{i=0}^n \sum_{j=0}^{m_i-1} L_{ij}(\theta_i, \phi_{ij}) A \cos \theta_i \Omega_{ij}. \quad (1)$$

All other conditions apply as in the parent method above.



9.12 LUMINOUS FLUX FOR COLOR-SIGNAL WHITE

ALIAS: color output, color light output

DESCRIPTION: We measure the luminous flux from an emissive display using the nonatle tri-sequence patterns (instead of a full-white screen) employing the same procedure as in the previous section, § 9.11 Units: lm, Symbol: Φ_{CSW} .

APPLICATION: In general, this measurement applies to all displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See § 5.4 Color-Signal White for full details.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use the nonatle tri-sequence patterns (e.g., NTSR*.PNG, etc.) as in Fig. 1 below.

PROCEDURE: Same as in § 9.11, but use the nonatle tri-sequence patterns (all three) and sum the resulting fluxes from each pattern:

$$\Phi_{CSW} = \Phi_R + \Phi_G + \Phi_B. \quad (1)$$

Note that if the luminance of the black screen is nontrivial, then a more accurate measurement is

$$\Phi_{CSW} = \Phi_R + \Phi_G + \Phi_B - 2\Phi_K, \quad (2)$$

where Φ_K is the flux from the full-black screen. This second equation helps account for the extra measurement of black subpixels on the screen whenever the display sequential contrast is less than 100:1.

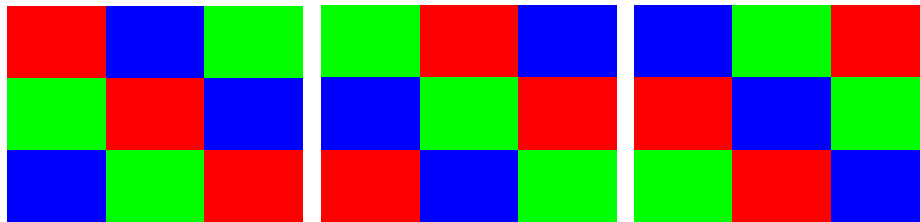


Figure 1. Nonatle tri-sequence patterns (NTSR, NTSG, NTSB, respectively). The flux is measured for each pattern Φ_R , Φ_G , Φ_B , respectively, and summed to get the total flux Φ_{CSW} from the primary colors.

ANALYSIS: Same as in § 9.11.

REPORTING: Same as in § 9.111.

COMMENTS: (1) **Same as in § 9.11.** Note that if the method § 9.11.1 Estimated Luminous Flux is employed when the tri-sequence patterns are used, then only a center measurement is made as described in the method. (2) **Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.



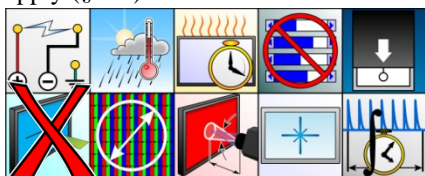
9.13 HORIZONTAL ANGULAR VIEWABILITY

ALIAS: normalized average horizontal viewing-angle contrast

DESCRIPTION: We measure the contrasts C_θ in the horizontal plane at the normal ($\theta = 0^\circ$) and at angles $\theta = \pm 15^\circ, \pm 30^\circ$, and $\pm 45^\circ$; we then average the contrasts and divide the result by the contrast at the normal and multiply by 100%. **Units:** none. **Symbol:** C_V .

This is a metric to permit a characterization of the viewing angle performance over a typical range of viewing angles that would be found in use by a family looking at television in a living room. It provides a single number that indicates how much the contrast degrades with and increasing viewing angle.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange for the luminance meter to measure the full-screen white and black from the specified angles.

PROCEDURE:

1. Measure the luminances of the white and black full screen at the normal: L_{W0} , L_{K0} .
2. Measure the luminances of the white and black full screen at angles $\theta = \pm 15^\circ$, $\pm 30^\circ$, and $\pm 45^\circ$: L_{W+15} , L_{K+15} , L_{W-15} , L_{K-15} , ..., L_{W-45} , L_{K-45} for a total of 12 luminance measurements at angles other than normal.

ANALYSIS:

1. Calculate the contrasts for each angle: $C_0 = L_{W0}/L_{K0}$, $C_1 = C_{+15} = L_{W+15}/L_{K+15}$, $C_2 = C_{-15} = L_{W-15}/L_{K-15}$, ..., $C_6 = C_{-45} = L_{W-45}/L_{K-45}$.
2. Sum the contrasts and obtain the average contrast C_{ave} :

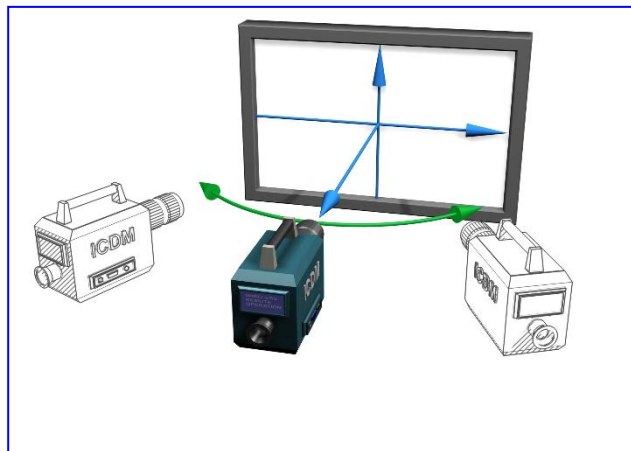
$$C_{\text{ave}} = \frac{1}{7} \sum_{i=0}^6 C_i.$$

3. Divide the average by the contrast C_0 at the normal and multiply by 100% to obtain the viewability:

$$C_V = 100\% \frac{C_{\text{ave}}}{C_0}.$$

REPORTING: As required, report the contrast at normal, C_0 , the average contrast C_{ave} , and the viewability C_V . Use no more than three significant figures for the contrast at normal and the average contrast; use only two significant figures for the viewability.

COMMENTS: (1) **Very High Contrasts:** If the black measurement is lower than $L_{\text{limK}} = 3.18 \times 10^{-3} \text{ cd/m}^2$, then use this limiting level L_{limK} for the black luminance value instead (see § 5.1).



—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Analysis example:			
Angle	L_W (cd/m ²)	L_K (cd/m ²)	Contrasts
0	347.2	0.487	712.9
+15°	297.2	0.642	462.9
-15°	285.8	0.598	477.9
+30°	220.1	0.973	226.2
-30°	206.4	0.982	210.2
+45°	145.2	1.234	117.7
-45°	136.9	1.334	102.6
		$C_{ave} =$	330.1
		$C_V =$	46 %

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example	
$C_0 =$	713
$C_{ave} =$	330
$C_V =$	46 %



9.13.1 EXTENDED HORIZONTAL ANGULAR VIEWABILITY

DESCRIPTION: We measure the contrasts C_θ in the horizontal plane at the normal ($\theta = 0^\circ$) and at angles $\theta = \pm 15^\circ, \pm 30^\circ, \pm 45^\circ, \pm 60^\circ$; and $\pm 75^\circ$; we then average the contrasts and divide the result by the contrast at the normal and multiply by 100%.

Units: none, **Symbol:** C_{EV} .

This is a metric to permit a characterization of the viewing angle performance over a very wide range of viewing angles that might be found in extreme viewing environments such as in a waiting room, lobby, or airport. It provides a single number that indicates how much the contrast degrades with and increasing viewing angle.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Arrange for the luminance meter to measure the full-screen white and black from the specified angles.

PROCEDURE:

1. Measure the luminances of the white and black full screen at the normal: L_{W0} , L_{K0} .
2. Measure the luminances of the white and black full screen at angles $\theta = \pm 15^\circ$, $\pm 30^\circ$, and $\pm 45^\circ$: L_{W+15} , L_{K+15} , L_{W-15} , L_{K-15} , ..., L_{W-75} , L_{K-75} for a total of 21 luminance measurements at angles other than normal.

ANALYSIS:

1. Calculate the contrasts for each angle: $C_0 = L_{W0}/L_{K0}$, $C_1 = C_{+15} = L_{W+15}/L_{K+15}$, $C_2 = C_{-15} = L_{W-15}/L_{K-15}$, ..., $C_{10} = C_{-75} = L_{W-75}/L_{K-75}$.
2. Sum the contrasts and obtain the average contrast C_{ave} :

$$C_{\text{ave}} = \frac{1}{11} \sum_{i=0}^{10} C_i.$$

3. Divide the average by the contrast C_0 at the normal and multiply by 100% to obtain the viewability:

$$C_{EV} = 100\% \frac{C_{ave}}{C_0}.$$

REPORTING: As required, report the contrast at normal, C_0 , the average contrast C_{ave} , and the viewability C_{EV} . Use no more than three significant figures for the contrast at normal and the average contrast; use only two significant figures for the viewability.

COMMENTS: Very High Contrasts: If the black measurement is lower than $L_{\text{limK}} = 3.18 \times 10^{-3} \text{ cd/m}^2$, then use this limiting level L_{limK} for the black luminance value instead (see § 5.1).

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Analysis example:			
Angle	L_W (cd/m ²)	L_K (cd/m ²)	Contrasts
0	347.2	0.487	712.9
+15°	297.2	0.642	462.9
-15°	285.8	0.598	477.9
+30°	220.1	0.973	226.2
-30°	206.4	0.982	210.2
+45°	145.2	1.234	117.7
-45°	136.9	1.334	102.6
+60°	124.1	1.442	86.1
-60°	122.5	1.478	82.9
+75°	98.72	1.534	64.4
-75°	94.51	1.622	58.3
		$C_{ave} =$	236.5
		$C_{EV} =$	33%

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example	
$C_0 =$	713
$C_{\text{ave}} =$	237
$C_{\text{EV}} =$	33 %



10. Temporal Measurements

Temporal measurements document the display performance changes with respect to time. The time periods involved can be very short for metrics such as jitter, longer for response time and flicker, or quite long for warm-up time and residual image. There are some overlaps in the metrics related to response time with those related to motion blur. We have tried to keep metrics with “non-moving” test patterns in the temporal measurement section, with references to related motion-artifact measurements where appropriate.

10.1. Warm-up Time

ALIAS

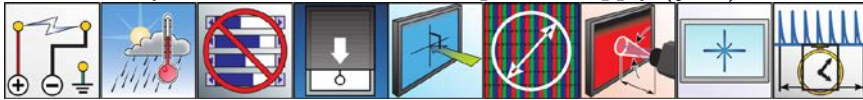
Time from turn-on to reach luminance stability

DESCRIPTION

Measure the time required to reach a stable luminance of $\pm 1\%$ (5 % maximum) per hour of operation or less using a white full-screen center measurement of the luminance.

SETUP

As defined by these icons. Standard setup details apply (§ 3.2)



Do not warm up the DUT prior to making these measurements! Arrange to display a white full screen and arrange to measure the center luminance of the screen as soon as the screen displays the white full-screen image. If the display had been on previously, wait three hours or longer with the display turned off before attempting a measurement of the warm-up time.

PROCEDURE

When the DUT is turned on record the time as t_0 . Measure L_1 at t_1 as soon as possible after a full white screen is displayed. Continue to measure the luminance L_i at time intervals of ten minutes or less (there is no objection to measuring more frequently and the intervals don't have to be the same); the time of the beginning of the measurement is t_1 , and t_i represents the times for the remaining L_i measurements. Try to record all times to an uncertainty of 10 s or less.

ANALYSIS

As the luminance approaches a stable value, look for the shortest time t_s where all the luminance values fall within $\pm 5\%$ of the final value for a duration Δt of one hour. Mathematically, t_s is the shortest time for which the following condition is valid for all L_i within the time interval t_s to $t_s + \Delta t$

$$L - \delta L \leq L_i \leq L + \delta L \quad (10.1)$$

where L is the final value of L_i at the end of the same interval $t_s + \Delta t$ and $\delta L = 0.05L$ (5% of the average).

REPORTING

Report the warm-up time in minutes to no more than two significant figures. If the warm-up time is measured to be less than 2 min, it is permissible to report the warm-up time in seconds.

COMMENTS

Before making measurements on the DUT, it is important that it has had sufficient time to reach operating stability. If this is not done, changes in performance might be attributed to some deficiency of the display and not because the warm-up was inadequate. Generally, the default 20-min warm-up time is adequate and will rarely have to be validated.



However, there may be situations which require a warm-up time measurement as when critical evaluations are needed that depend upon a stable display.

In reality, absolute luminance stability can never be achieved since there are long-term stability and life issues associated with displays. Luminance will often decay over the lifetime of the display. In some cases, luminance may actually increase in time for some life of the display before the life degrading cycle begins. Small luminance changes over long periods such as these are ignored for warm up.

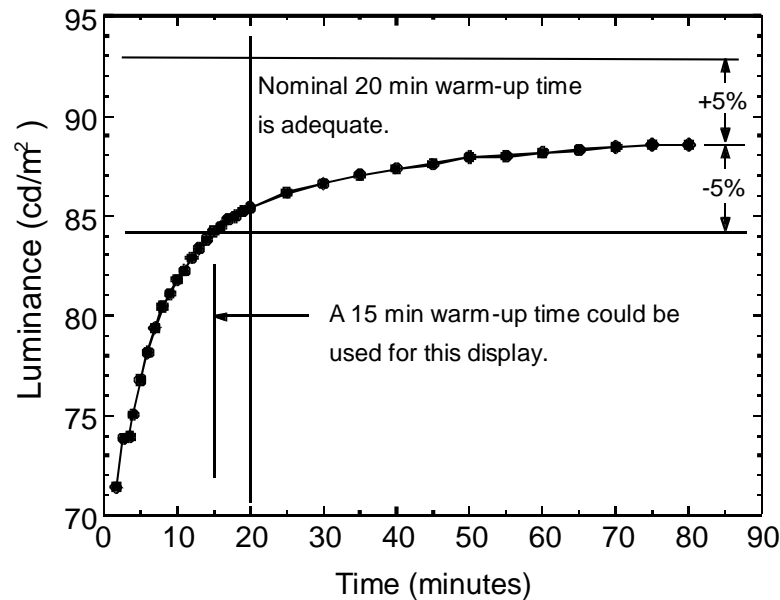


FIGURE 10.1. Example of a warm-up measurement. Sample data only – do not use any values shown to represent expected result of your measurement.

10.2. Response time metrics

The response time of a display is a measure of how fast the display can transition from one gray shade to another. A slow response time can greatly affect the display of animation or motion video as well as the ability to follow a moving cursor.

We begin this section with a general introduction to response time measurement. The next section describes the detailed measurement of the temporal step response or simply step response. This is followed by sections that describe specific metrics based upon selection of test patterns and analysis of the step response. The first of these is what we have called total response time. Total response time is the classic measurement of display response time which is the time for a display to switch from black to white and back to black again. The next metric is gray-to-gray response time which has become important because of the fact that for many LCDs, the response time between gray levels can be much slower than the response time between black and white. Finally, we discuss Gaussian response time that is a variation of gray-to-gray response time that uses a different analysis technique to achieve improved measurement repeatability.

The basic procedure for response time measurement is to apply a time varying (blinking) test pattern to the DUT while measuring the time-varying relative luminance output of the display with a high speed LMD. The acquired data is the step response of the display. The step response is filtered, as necessary, and analyzed to determine the response time. The response time is often referred to as the time that it takes for the display to transition from 10% to 90% of the initial and ending relative luminance levels.

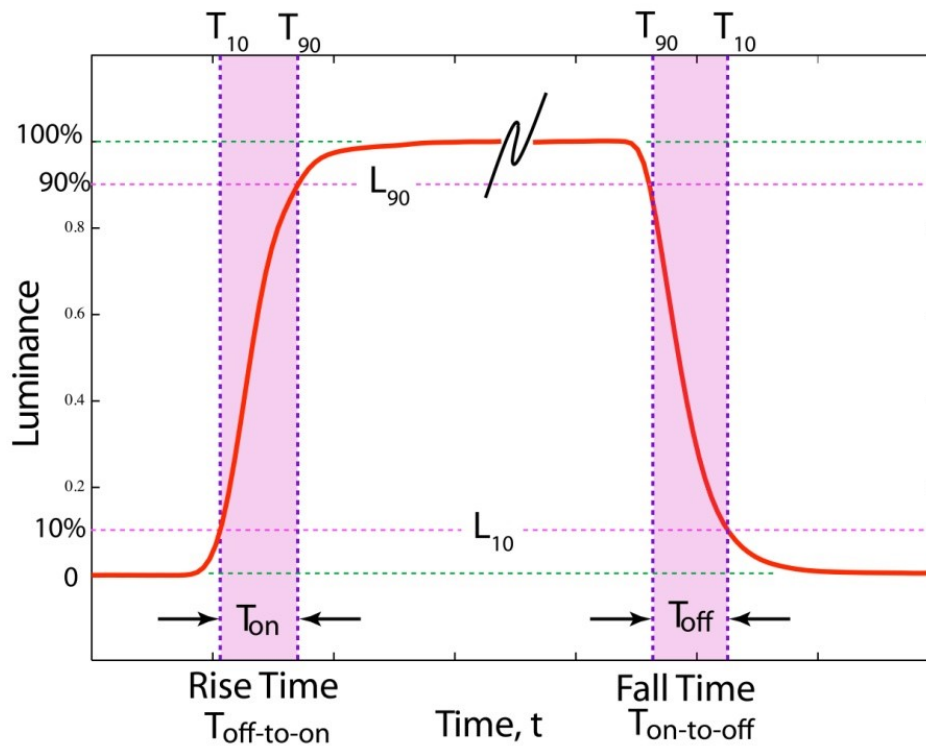


FIGURE 10.2. Example of a response time measurement. Sample data only – do not use any values shown to represent expected result of your measurement.

Note: Response-time is an electro-optical characteristic of a display and does not necessarily correlate with motion blur. Please consider Moving-edge blur and Blur Edge Time (IDMS 12.4.1) when comparing display-induced motion blur.



I see flicker and you don't. Now what do we do?



It says here for you to leave the room.



10.2.1. Temporal step response

DESCRIPTION

Here we measure the step-response resulting from pixel activation-deactivation. This forms the basis of the other response-time measurements that follow.

Note: This is *not* the response time that includes both rise and fall times. This is only the measurement and analysis of a single step. It applies to a number of measurement methods in this document.

SETUP

As defined by these icons, standard setup details apply (§ 3.2).



The test patterns and LMD should meet the requirements outlined below.

Test Pattern

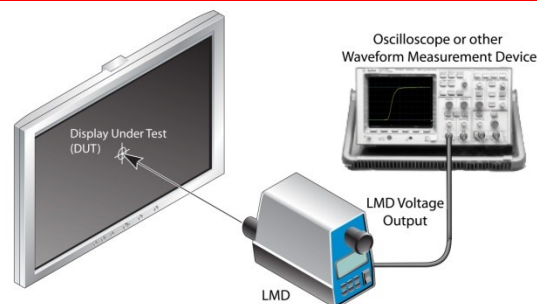
Typically, some form of blinking test pattern is used for response time measurement. Historically, the standard test pattern for response time measurement blinks between two full-screen gray levels V_{start} and V_{end} . A blinking box or blinking line test pattern may be more appropriate, especially as response times decrease.

The shape, position, color, intensity, and blink rate of an appropriate test pattern depends on the display technology, and should satisfy the following requirements:

1. The test pattern blink rate should be slow enough to ensure that the display reaches the steady-state relative luminance associated with gray levels V_{start} and V_{end} . If this requirement cannot be met, the relative luminance of gray level V_{start} and V_{end} may be measured separately as long as they do not drift significantly during the measurements.
2. The test pattern may be smaller than the measurement field if the filtered luminance contribution of the background (measurement field not covered by the test pattern) is constant. Non-constant backgrounds may alternatively be removed using image-processing techniques (not covered in this document—"an exercise for the student").
3. When multi-pixel test patterns are generated and displayed in a raster based display system, it is possible for the test pattern update to be occasionally split across two or more display refresh cycles (an effect known as "tearing"). When tearing cannot be eliminated (by techniques such as frame-synchronous palette switching), it should be reduced as much as practical by using targets with a small number of rows or an LMD with a small measurement field. Anomalous large measurements of response time caused by tearing should be discarded.
4. Even within a single display refresh cycle, some time is typically required to electrically address/command the pixels in the test pattern from the on state to the off state. The test pattern update time T_{TPU} is the time between the first and last pixel updates within the LMD measurement field. T_{TPU} should be shorter than the minimum transition time. The size, and shape of the test pattern or LMD measurement field affect T_{TPU} . The T_{TPU} can be estimated from the display horizontal line time multiplied by the number of lines subtended by the LMD measurement field. Note also that the test pattern should not span the seam on dual-scanned displays or tiled displays, since this may cause T_{TPU} to equal the refresh time T_f .

LMD

The LMD should be capable of producing a linear response to rapid changes in luminance. The LMD response time T_{LMD} and sample time should be significantly shorter than the minimum transition time. The LMD need not be dark-





field corrected and does not require photopic correction unless the color of the test pattern changes significantly as it changes between L_W (full white) and L_K (full black).

Fast-response displays

Both T_{TPU} and T_{LMD} place limits on the transition time that can be measured. Ideally T_{TPU} and T_{LMD} should be one-tenth the transition time being measured:

$$T_{TPU}, T_{LMD} < 0.1 \times \min(T_{on}, T_{off}) \quad (10.2)$$

For some very fast-response displays (OLED or LED) it may not be possible to meet these conditions. In this case it should be noted that the response times reported exceed the capability of the measurement setup.

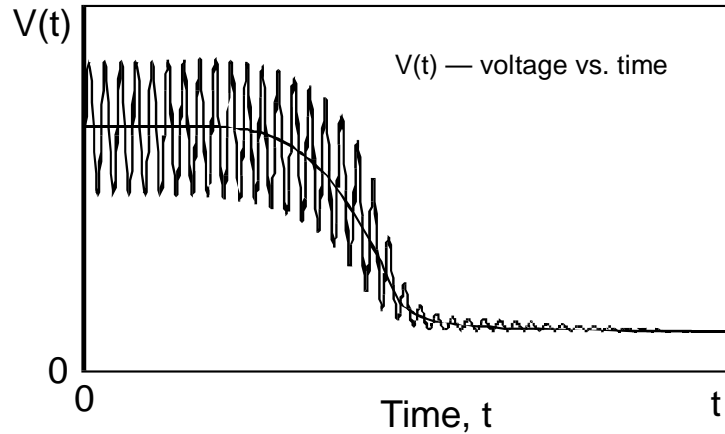


FIGURE 10.3. Example of a temporal step response measurement. Sample data only – do not use any values shown to represent expected result of your measurement.

PROCEDURE

As the display transitions from levels V_{start} to V_{end} , the LMD samples the light

$$L_n = L(t_n), n = 1, 2, \dots, N \quad (10.3)$$

as a function of time are typically collected, stored, processed, and displayed by a storage device such as a computer or storage oscilloscope with Δt as the time separation between collected samples. See the appendix §A3.3 Detector Linearity Diagnostic and §A8 Temporal Response Diagnostics for more information. Be sure that sufficient time is spent recording the starting and ending levels so that the steady-state performance is characterized.

ANALYSIS

The acquired output from the LMD may contain a significant amount of noise. This noise includes random noise internal to the LMD and ripple caused by display backlight modulation or display refresh. Though ripple is not truly noise in the sense that it is actually part of the display luminance output, it is not a desired part of the response time measurement, and it affects the repeatability of the response time measurement. Two common methods of reducing the effects of ripple are to (1) apply a ripple filter such as a tuned moving-window-average filter; or (2) fit the data to a curve such as a cumulative Gaussian or exponential function (see 10.2.4 Fitted Response Times).

We construct a tuned moving window average filter (assuming a digitized output of the LMD): Let the ripple period be τ , the LMD sample rate be s (samples per second), let the raw time-dependent light measurements taken at intervals of $\Delta t = s^{-1}$ be L_n , and let ΔN be the number of light data points collected during the ripple period $\Delta N = \tau s$, then the resultant moving-window-average-filtered signal S_i is given by



$$S_i = \frac{1}{\Delta N} \sum_{n=i}^{n=i+\Delta N-1} L_n \quad (10.4)$$

See the appendix B18 Digital Filtering by Moving Window Average for more information. Note that the moving-window-average filter is the same as convolving the step response signal with a pulse with width equal to ΔN . If the filter width is equal to one video frame, the filtered waveform is equivalent to the moving-edge temporal profile (METP – § 12.1.2 Motion Blur from Temporal Step Response).

The moving window average filter will distort or increase the response time. This distortion can be accounted for by multiplying the filtered response time by a correction factor $f_c(x)$ from the table in FIGURE 10.4. The correction factor is selected based on the ratio of the width of the moving window average filter and the measured (filtered) response time ($T_{90} - T_{10}$):

$$x = \frac{T_{MA}}{(T_{90} - T_{10})}, \text{ where } T_{MA} = \frac{\Delta N}{s} = \tau \quad (10.5)$$

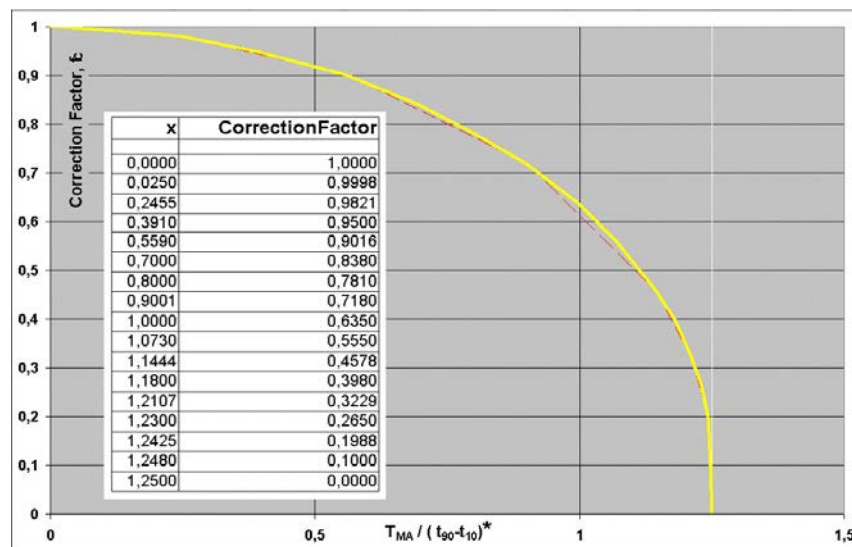


FIGURE 10.4. Correction factor.

PROCEDURE

1. Change the test pattern from gray level V_i to gray level V_j .
2. Position the LMD and adjust the measurement field, if possible, to cover the smallest area of the display while still obtaining a measurable signal.
3. Using an oscilloscope or data acquisition card connected to a computer, acquire the time-varying relative luminance of the display. This is the step response curve. The step response curve should include the steady state reference levels L_0 and L_{100} representing the relative luminance of gray levels V_i and V_j . If the acquisition can be accurately synchronized to the display transition through an electrical trigger signal, multiple acquisitions may be acquired, and the waveforms averaged to reduce random noise in the step response.

ANALYSIS

Refer to the following sections for analysis and metrics derived from the step response measurement results.

REPORTING

Report the test pattern used (position, size, color, and blink on/off times), the LMD sample rate, the filtering used (if any), the smoothing used, and the smoothed transition profile. Also report the LMD measurement field and working distance (or display lines subtended by the LMD), and aperture type (circular or other geometry).



10.2.2. Response time

ALIASES

Total Response Time, Image Formation Time

DESCRIPTION

Measure the time for a display to change from black to white, and to black again. That is the full-on and full-off step of the display. They are added together to produce the total response time.

APPLICATION

Most types of displays and in any state of development. Most prevalent for LCDs.

SETUP

As defined by these icons, standard setup details apply (section 3.2).



Use an LMD with adequate time to resolve the response time, $10 \times$ faster or more than the fastest response time to be measured. The LMD must also have a luminance-to-voltage output to capture the step response waveform.

Capture the optical rise or fall time from the LMD so that analysis of the rise or fall duration can be performed. For example, an oscilloscope could be connected to the luminance-to-voltage output of the LMD. Alternate methods to reproduce the optical rise/fall characteristics might be analog-to-digital converters (digitizer type waveform capture). Typically, this will produce a waveform to be part of the time analysis.

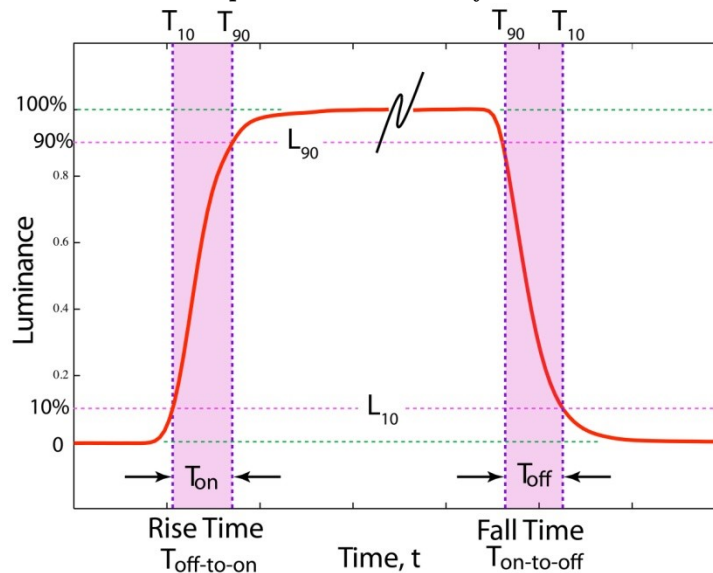


FIGURE 10.5. Rise and fall time.

PROCEDURE

1. Use a full black screen (off) and then switch it to white (on) at the frame rate. Assure that the switching time is slow enough for the level transition to reach its full level.
2. Use black and white test patterns:
 V_K = black and V_W = white. Measure the black-to-white transition on the optical characteristic analyzer and determine the time from the 10% to 90% points. Similarly, determine the time from 90% to 10% of the white to black transition. That is the fall time.
3. Capture the step response according to the previous section, § 10.2.1 Temporal step response.



ANALYSIS

Apply ripple filters as necessary. Calculate $L_{\text{range}} = L_W - L_K$, $L_{10} = 0.1L_{\text{range}} + L_K$ and $L_{90} = 0.9L_{\text{range}} + L_K$. Find the times T_{10} , T_{90} at which the step response equals L_{10} , L_{90} using linear interpolation between the bounding data points) and record $T_{\text{rise}} = T_{90} - T_{10}$. In a similar way measure and record $T_{\text{fall}} = T_{10} - T_{90}$. Calculate the response time $T_{\text{response}} = T_{\text{rise}} + T_{\text{fall}}$.

REPORTING

Report the rise time T_{rise} , the fall time T_{fall} , and the response time T_{response} .

COMMENTS

1. **Pattern Conditions:** Use full screen for black and white levels if no luminance loading occurs. For displays with luminance loading assure the percentage of white is at the maximum luminance.
2. **Pattern Conditions:** Switching from black-to-white or white-to-black can be separate measurements. Or if the black-white pattern is continually switching and is switched slowly, *e.g.*, $10 \times$ slower than the response, the rise and fall times may be seen on the same oscilloscope trace. Either method will produce the same results.
3. **Modulation:** If there is modulation (or noise) that interferes with clearly obtaining the 10% and 90% points then refer to the Analysis section of 10.2 Response time metrics.

10.2.3. Gray-to-Gray Response Time

ALIASES

Gray-Level Response Time, Inter-Gray Level Response Time, G-G Response Time

DESCRIPTION

For some display technologies, especially LCDs, the response time for small gray-to-gray transitions can be much larger than the black to white response time. Here we measure the rising or falling times of the temporal step response resulting from various gray-to-gray transitions (including black and white), and report the min, max and average of these measurements. For this measurement, the response time refers to a single gray-to-gray transition (either rise time or fall time). Units: s, ms.

SETUP

As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE

1. Set-up to measure the step-response according to 10.2.1 Temporal step response.
2. *Select gray level set.* Select a set of M gray levels V spanning the range from V_K to V_W . These may include all gray levels or may be equally spaced in gray level, in luminance, or in lightness (Appendix B26). One example of equal lightness steps are the gray levels $V = \{0, 31, 63, 95, 127, 159, 191, 223, 255\}$. In the example pictured, this yields a matrix, with $M(M - 1) = 9 \times 8 = 72$ non-zero transitions.
3. Acquire the step response for each of the possible pairings of gray levels.

TABLE 10.1. Reporting example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

T_{rise}	2.2 ms
T_{fall}	12.5 ms
T_{response}	14.7 ms

Response Time, 9x9

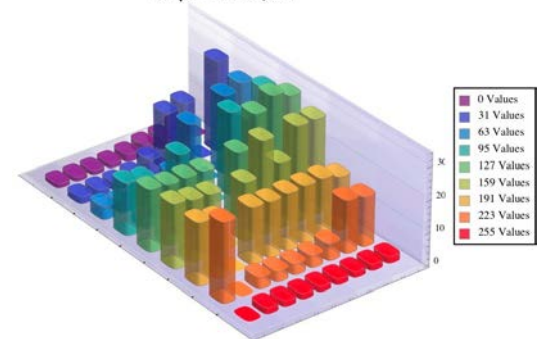




TABLE 10.2. Gray-to-gray response time reporting example (unit: ms).

Sample data only: Do not use any values shown to represent expected results of your measurements.

End grey level										
Start grey level	Level	0	31	63	95	127	159	191	223	255
	0	0	1.86	1.67	1.69	1.69	1.76	1.78	1.94	2
	31	24.44	0	3.45	3.21	3.22	3.66	5.08	16.31	15.3
	63	19.2	18	0	17.52	17.15	17.63	17.88	18.02	16.4
	95	19.85	18.86	18.51	0	18.04	28.65	19.76	29.13	29.1
	127	19.26	18.57	18.58	18.55	0	20.13	30.05	33.63	31.7
	159	16.21	15.14	5.98	18.69	6.55	0	25.7	21.85	29.2
	191	4.04	3.32	3.04	3.16	5.92	19.22	0	24.26	26.3
	223	2.1	2.27	2.33	2.74	5.53	18.03	19.11	0	28.5
	255	1.32	1.3	1.31	1.48	2.28	3.4	3.79	5.28	0

ANALYSIS

For each step-response curve apply ripple filters as necessary to minimize noise or ripple that might interfere with determining the correct rise or fall times. Calculate $L_{\text{range}} = L_W - L_K$, $L_{10\%} = 0.1L_{\text{range}} + L_0$ and $L_{90\%} = 0.9L_{\text{range}} + L_0$. Find the times T_{10} , T_{90} at which the step response equals $L_{10\%}$, $L_{90\%}$ (using linear interpolation between the bounding data points) and record $T_{\text{rise}} = T_{90} - T_{10}$. In a similar way, measure, and record $T_{\text{fall}} = T_{10} - T_{90}$.

REPORTING

Report the number of gray-levels M , gray level spacing, test pattern used (position, size, color, and blink on/off times), the LMD sample rate, and the filtering used (if any). Record the rise or fall times in a table arranged according to starting and ending gray levels. It is often helpful to graph the data in a 3-dimensional chart as shown above. Report the minimum, maximum, and average response times of all of the gray-to-gray transitions. Note: when reporting the average do not include the null transitions along the diagonal of the table.

COMMENTS

- Pattern Conditions:** Use full screen patterns for gray levels if no luminance loading occurs. For displays with luminance loading (or dynamic backlighting) use a test pattern that blinks a small rectangular region of the screen.
- Filtering:** Noise is a significant problem when measuring gray-to-gray response time. Often the noise and display ripple are larger than the gray-to-gray luminance transition being measured. Tuned moving-window-average filters have been shown to be effective especially when combined with techniques to remove response time distortion (see § 10.2.1 Temporal Step-Response above). Curve fitting techniques have also been effective (see § 10.2.4 Fitted Response Time).

TABLE 10.3. Reporting example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

T_{min}	1.303 ms
T_{max}	33.63 ms
T_{average}	13.3 ms
Number of gray levels (M)	9



10.2.4. Fitted Response Times

DESCRIPTION

Response time measurement based upon direct measurement of the 10% and 90% point of a temporal step response (TSR) is subject to issues with repeatability that may result from anomalies in the TSR waveform. By fitting the data to an appropriate model function more repeatable results may be obtained. Two simple model functions that may be used are the cumulative Gaussian and a decaying exponential. The following sections describe these measurements in more detail. Other more complex mathematical models, such as models of liquid crystal temporal behavior, may be used as well.

PROCEDURE

1. Set-up to measure the step response over a range of gray-levels according to previous §10.2.3 above.
2. Fit the acquired waveforms with the appropriate model function using a non-linear least-squares method.
3. Compute the transition time (rise or fall time) in ms from the model function.

10.2.4.1. Gaussian Response Time

ALIAS

Gray-to-gray response time, fitted response time

DESCRIPTION

Measure the gray-to-gray response times by fitting a cumulative Gaussian function to the step response. Derive the metric Gaussian response time (GRT) from the estimated standard deviation of the Gaussian. The metric GRT is analogous in expected value to the rise time or fall time but is a more robust measurement. It does not rely on arbitrary filtering of the waveform or problematic methods of estimating intersections of the waveform with 10% and 90% values.

SETUP

As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE

1. Set-up to measure the step response over a range of gray-levels according to 10.2.3.
2. Fit the acquired waveforms with a cumulative Gaussian function using a non-linear least-squares method such as Levenberg-Marquardt. The function has the form:

$$\begin{aligned}
 G(t) &= R_{\text{start}} + (R_{\text{end}} - R_{\text{start}}) \int_{-\infty}^t \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \\
 &= R_{\text{end}} + \frac{(R_{\text{start}} - R_{\text{end}})}{2} \operatorname{erfc}\left(\frac{t - \mu}{\sigma\sqrt{2}}\right),
 \end{aligned} \tag{10.6}$$

where R_{start} and R_{end} are starting and ending relative luminance values, t is time in milliseconds, μ is the location of the midpoint of the edge transition, σ is the standard deviation of the fitted Gaussian, and erfc is the complimentary error function.

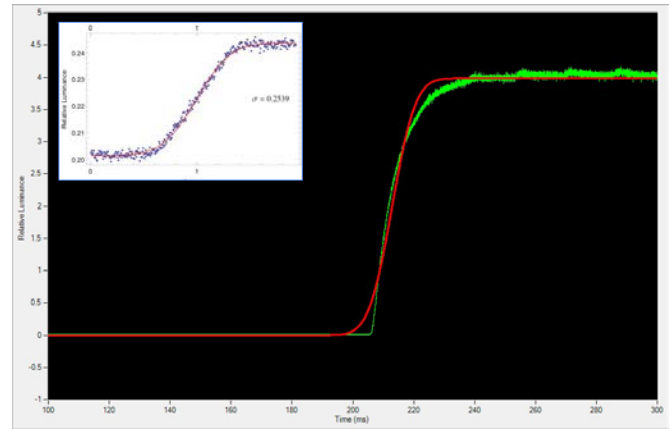


FIGURE 10.6. Examples of Gaussian curves (red) fitted to a step response (green, blue in insert) to estimate rise times.



3. (Optional) Truncate the waveform at $\mu \pm 4\sigma$ and repeat the fit. This reduces the influence of noise and drift far from the actual edge.
4. Compute the transition time (rise or fall time) in ms from σ (in ms) using the formula $t_{\text{transition}} = 2.563\sigma$.
5. Measure and record the rise or fall time of each of the possible pairings of gray levels. Each transition can be measured individually, or if using a test pattern that blinks between two gray-levels it is possible to capture two transitions (both the rise and fall time) with one measurement. Rise times lie on one side of the diagonal in the table and fall times lie on the other side.

REPORTING

Report the number of gray-levels M , gray level spacing, test pattern used (position, size, color, and blink on/off times), the LMD sample rate. Record the rise or fall times in a table arranged according to starting and ending gray levels. It is often helpful to graph the data in a three-dimensional chart as shown. Report the minimum, maximum, and average response times of all of the gray-to-gray transitions. Note: when reporting the average do not include the null transitions along the diagonal of the table.

COMMENTS

1. **Pattern Conditions:** Use full screen patterns for gray levels if no luminance loading occurs. For displays with luminance loading (or dynamic backlighting) use a test pattern that blinks a small rectangular region of the screen.
2. **Fitting:** Fitting the measured values to the cumulative Gaussian serves as both a filter and as an estimate for the transition time. In many cases the cumulative Gaussian is not a perfect fit. The top and bottom corners of the cumulative Gaussian are symmetric, and the actual step response in many cases is not. However, the Gaussian fit still serves as a robust estimate of the rise or fall time. For the curve fit to converge to a solution it is often necessary to provide reasonable estimates for R_{start} , R_{end} , and μ .

TABLE 10.4. Reporting example of Gaussian response time data.

Sample data only: Do not use any values shown to represent expected results of your measurements.

t_{min}	9.4 ms
t_{max}	29 ms
t_{average}	17.2 ms
Number of gray levels (M)	7

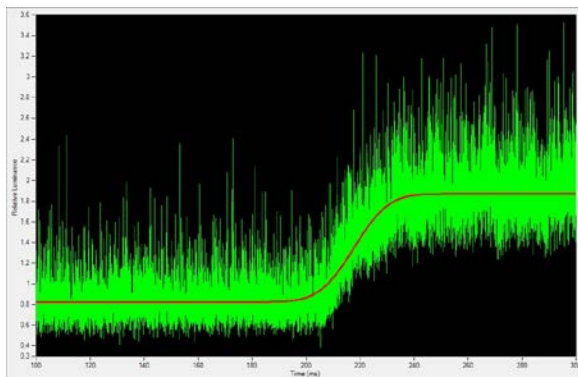


FIGURE 10.7. Example of Gaussian curve (red) fitted to noisy response (green) to estimate rise time.



Your specs say a backlight life of 300000 hours...?! What life metric did you use?



Um... we measured it at one hour and then again at two hours and extrapolated to zero luminance.



10.2.4.2. Exponential Response Time

ALIAS

Gray-to-gray response time, fitted response time

DESCRIPTION

Measure the gray-to-gray response times by fitting a decaying exponential function to the step response. Derive the metric exponential response time (ERT) from the time constant of the exponential. The metric ERT is analogous in expected value to the rise time or fall time but is a more robust measurement. It does not rely on arbitrary filtering of the waveform or problematic methods of estimating intersections of the waveform with 10% and 90% values.

SETUP

As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE

1. Set-up to measure the step response over a range of gray-levels according to 10.2.3.
2. Fit the acquired waveforms with a decaying exponential function using a non-linear least-squares method such as Levenberg-Marquardt. The function has the form:

$$G(t) = R_{\text{start}}, t \leq t_0 \quad (10.7)$$

$$G(t) = R_{\text{end}} + (R_{\text{start}} - R_{\text{end}})e^{-\lambda(t-t_0)}, t > t_0 \quad (10.8)$$

3. Where R_{start} and R_{end} are starting and ending relative luminance values, t is time in milliseconds, λ is the time constant for the exponential, and t_0 is the time to the beginning of the transition. Compute the transition time (rise or fall time) in milliseconds from λ using the formula:

$$t_{\text{transition}} = \frac{\ln 0.9 - \ln 0.1}{\lambda} = \frac{2.197}{\lambda} \quad (10.9)$$

4. Measure and record the rise or fall time of each of the possible pairings of gray levels. Each transition can be measured individually, or if using a test pattern that blinks between two gray-levels it is possible to capture two transitions (both the rise and fall time) with one measurement. Rise times lie on one side of the diagonal in the table and fall times lie on the other side.

REPORTING

Report the number of gray-levels M , gray level spacing, test pattern used (position, size, color, and blink on/off times), the LMD sample rate. Record the rise or fall times in a table arranged according to starting and ending gray levels. It is often helpful to graph the data in a three-dimensional chart. Report the minimum, maximum, and average response times of all of the gray-to-gray transitions. Note: when reporting the average do not include the null transitions along the diagonal of the table.

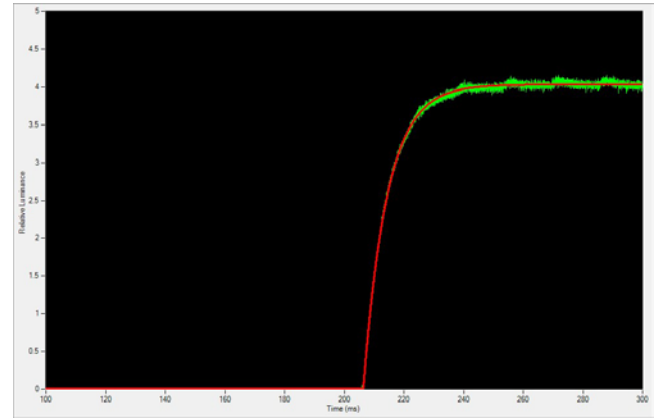


FIGURE 10.8. Example of exponential curve (red) fitted to the step response (green) to estimate rise time.



COMMENTS

1. **Pattern Conditions:** Use full screen patterns for gray levels if no luminance loading occurs. For displays with luminance loading (or dynamic backlighting) use a test pattern that blinks a small rectangular region of the screen.
2. **Fitting:** Fitting the measured values to the decaying exponential serves as both a filter and as an estimate for the transition time. In some cases, the exponential provides a better fit than the cumulative Gaussian because the top and bottom corners of the decaying exponential are not symmetric. For the curve fit to converge to a solution it is often necessary to provide reasonable estimates for R_{start} , R_{end} , and t_0 .

Table 10.5. Reporting example of exponential response time data.

Sample data only: Do not use any values shown to represent expected results of your measurements.

t_{\min}	9.4 ms
t_{\max}	29 ms
t_{average}	17.2 ms
Number of gray levels (M)	7

10.3. Video Latency

ALIAS

Input Lag, Processing Delay, Latency

DESCRIPTION

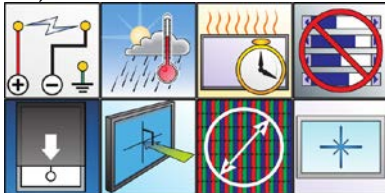
We measure the time for the display to respond to an input signal, including any processing-induced latency, or the time for the luminance for the display to turn on from the time it is triggered to do so. We measure from the trigger time until the time the luminance reaches 50% of the full luminance at the center of the screen. We average over multiple measurements and report this as the video latency.

APPLICATION

Display technology independent. Will apply primarily to fully enclosed display systems being driven by external sources to include all processing delays which may add latency to change the display content.

SETUP

As defined by these icons. Standard setup details apply (§ 3.2)



Use a pattern that switches from black to white when triggered. Use full screen for black and white levels if no

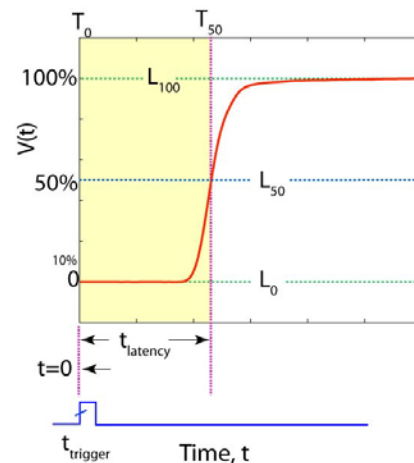
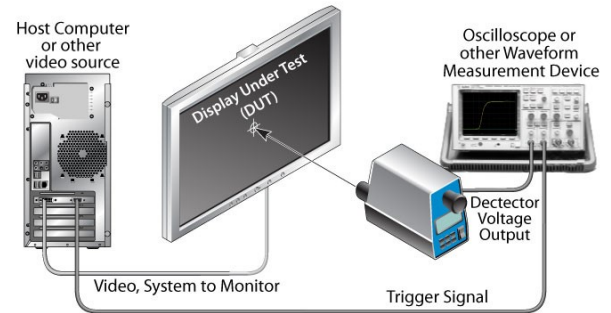


FIGURE 10.9. Example of exponential curve (red) fitted to the step response (green) to estimate rise time.



luminance loading occurs. For displays with luminance loading assure the percent of white is at largest size to achieve the maximum luminance and is centered.

PROCEDURE

1. Establish a trigger point, i.e., the time at which the change of state from black to white is to be initiated in the host system. The trigger point is $t = 0$.
2. Measure the time varying luminance at the center of the display using a photo detector.
3. Record the time varying voltage signal from the photo detector using an oscilloscope or data acquisition device.
4. Change the displayed pattern from black to white and measure the change over time.
5. Repeat the measurement multiple times.

ANALYSIS

With the display in the black state record the voltage from the photo detector as the 0% level. Command the display to change to white. Trigger the data acquisition based upon the command. Record the luminance from the trigger to the time where full white is achieved. Record the photo detector voltage at full-white as 100%.

REPORTING

Report the time from the trigger point to the point that the luminance reaches 50% of full white.

$$t_{\text{latency}} = t_{50} - t_0 \quad (10.10)$$

Make multiple measurements of latency and record the minimum, maximum, and average latency.

Table 10.6. Reporting example of display system video latency data.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Minimum $t_{\text{latency}} (t_{50} - t_{\text{trigger}})$	12.2 ms
Maximum $t_{\text{latency}} (t_{50} - t_{\text{trigger}})$	28.9 ms
Average $t_{\text{latency}} (t_{50} - t_{\text{trigger}})$	20.6 ms

COMMENTS

1. **Filtering:** Do not use any smoothing or filtering which can impact the amplitude or rise or fall times.
2. **Trigger:** Obtaining the trigger signal may require access to electrical signals inside the display or video source electronics. The selection of an appropriate signal is application specific. Optical triggers *cannot* be used since they would mean the trigger is measured on the display.
3. **Measurement location:** Latency highly depends on the location of the photo detector on the display surface. This is because most displays are refreshed in a raster fashion from top to bottom. There can be almost one frame time difference in latency for measurements made at the top of the display versus the bottom. The center of the display is the recommended measurement location for this test; however, other locations such as the first line of the display may be desired for some applications. The measurement location, if not at the center, should be noted in the report.



10.4. Residual Image

ALIAS

latent image, burn-in, image retention, image sticking

NOTE: This measurement can cause irreparable damage to the display.

DESCRIPTION

Measure the residual image of a high-contrast checkerboard.

Units: None, results are contrasts. **Symbols:** R_W for white, R_B for black.

This is a measurement of how the screen is affected by long-term static images. We will see how a long-term static 5×5 checkerboard affects the display of a full-white screen and a full-black screen. Initially, we will measure the full screens of both white and black at three locations to account for any luminance non-uniformities. We then burn in the checkerboard pattern. Finally examine full screen white and black to see if there is any residual image.

SETUP

As defined by these icons, standard setup details apply (3.2).



OTHER SETUP CONDITIONS

Full-screen white, full screen black, and 5×5 checkerboard patterns. Arrange to measure the display at three points left of center a distance of the checkerboard box width, at center, and right of center a distance of a box width.

Depending upon how uniform the screen is, it may be necessary to measure at the exact same three locations throughout the procedure. This will require a reproducible positioning of the LMD relative to the screen. You will need to display a white full screen, a black full screen, and a 5×5 checkerboard pattern of black and white boxes with a black box at the center and box size of $1/5$ of the screen.

PROCEDURE

- Initial Measurements:** Display a white full screen and measure the center luminance L_{WC} and the luminance on each side of center L_{WR} and L_{WL} (for right and left) a distance of 20 % ($0.2H$) of the screen horizontal width H . Similarly, display a full black screen and measure the luminances L_{BC} , L_{BR} , L_{BL} at the same three locations.

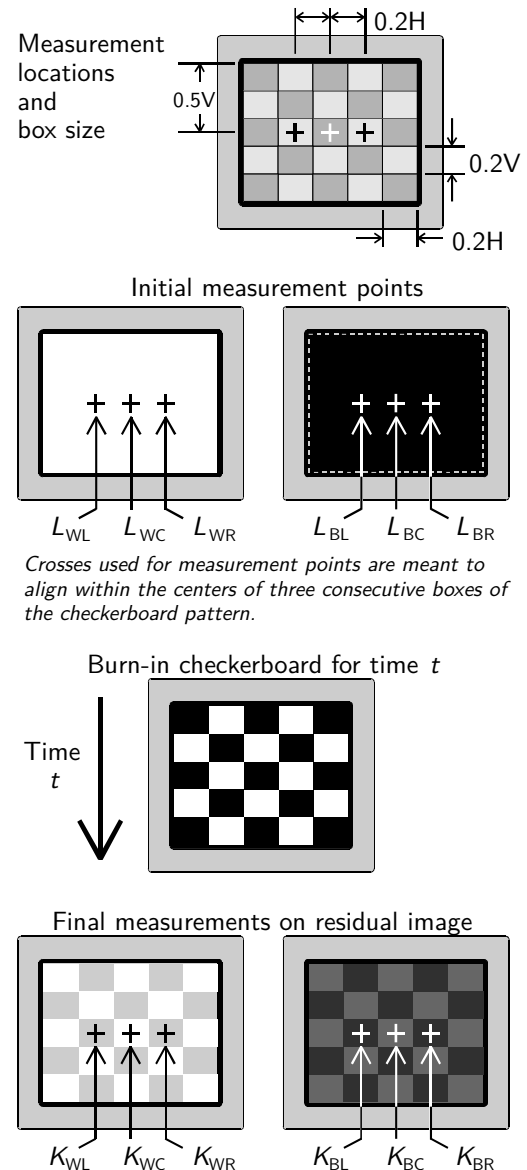


FIGURE 10.10. Note: This figure is not intended to represent any real or anticipated situation. Make no inferences from the shades pictured here.



2. **Burn-in:** Burn-in the checkerboard image by allowing it to remain displayed continuously for a certain number of hours t agreed to by all interested parties (the number of hours t is reported). Near the end of the burn-in time align the LMD to measure at the same three locations.
3. **Final Measurements:** At the end of the burn in time, switch the DUT directly from a checkerboard to a white full screen, after a time interval upon which all interested parties agree t_R (or as soon as possible) measure the luminance at the three locations (center, right, left) K_{WC} , K_{WR} , K_{WL} . Then switch the display to a black full screen and measure the luminances at the three locations (center, right, left) K_{BC} , K_{BR} , K_{BL} . These measurements should be made in as small a time as is easily as possible.
4. **Recovery:** There is no set way to recover from a residual image. Recovery procedures range from maintaining a full-screen white for a long period of time, displaying a changing series of images, to displaying the negative image of the image that originally produced the residual image. The manufacturer should be contacted for any possible recovery technique.

ANALYSIS

In what follows, we will be using ratios of these luminance values to obtain contrasts. By using ratios, we eliminate the effects of overall luminance degradation of the display from either an extended warm-up period or from aging. We also need to account for any nonuniformity inherent in the screen for the three measurement points. The residual image factors are defined as follows:

Residual Image Factors:

$$R_W = \frac{\max[(K_{WR} + K_{WL})L_{WC}, (L_{WL} + L_{WR})K_{WC}]}{\min[(K_{WR} + K_{WL})L_{WC}, (L_{WL} + L_{WR})K_{WC}]} \quad (10.11)$$

$$R_B = \frac{\max[(K_{BR} + K_{BL})L_{BC}, (L_{BL} + L_{BR})K_{BC}]}{\min[(K_{BR} + K_{BL})L_{BC}, (L_{BL} + L_{BR})K_{BC}]} \quad (10.12)$$

The above equations take into account compensation for non-uniformities inherent in the screen for the three measurement points for both black and white screens. R_W is the contrast in the residual image for the white screen and R_B is the contrast in the residual image for the black screen. (See comments below for a more detailed explanation.)

REPORTING

Report the burn-in time t in hours (the agreed upon time interval, in the examples we show 5 hours as an illustration only), the measurement time after burn-in (t_R), and the measured residual image contrasts of white R_W and black R_B to no more than three significant figures.

COMMENTS

This measurement, as described, does not account for sensitivity of residual images from colors or gray scales. Be sure to use a small enough measurement aperture to be completely contained within a checkerboard measurement box area. It is suggested that at least 20 % of the measured area should extend past the measurement aperture area on all sides. The luminances for the white and black screens at the center and on each side of the center must be measured in the same time frame (within a few minutes). It cannot be measured before the end of the burn-in period. The residual image factors may not be uniform over the entire display area. Areas with the most pronounced amount of residual image should be assessed. If it appears to generally be uniform, then measuring at the center of the screen and the adjacent boxes is preferred.

It will be noted that the residual image metrics (R_W and R_B) are insensitive to the algebraic sign of the change in the luminance from the burn-in. If that were not the case, then there could arise a technology dependence in the metric;

TABLE 10.7. Example analysis.
Sample data only: Do not use any values shown to represent expected results of your measurements.

Quantity	Value
L_{WC}	132.1
L_{WR}	124.5
L_{WL}	123.2
L_{BC}	0.967
L_{BR}	0.923
L_{BL}	0.932
t	5 h
t_R	ASAP
K_{WC}	105.9
K_{WR}	88.8
K_{WL}	89.4
K_{BC}	0.953
K_{BR}	0.796
K_{BL}	0.772
R_W	1.1143
R_B	1.1659



for example, it would make FPDs seem different from CRTs, and hence be an obstacle to comparing FPDs and CRTs on a level playing field.

The above equations for R_W and R_B are a little more transparent if we assume a perfectly uniform screen for which we will let L_W be the uniform white luminance of the unperturbed screen where $L_{WR} = L_{WL} = L_{WC} = L_W$; L_B be the luminance of the unperturbed black screen so that $L_{BR} = L_{BL} = L_{BC} = L_B$; K_W be the burned-in luminance of white outside of center so that $K_{WR} = K_{WL} = K_W$; and K_B be the burned-in luminance of black outside the center so that $K_{BL} = K_{BR} = K_B$. Then the Eqs. (10.11) and (10.12) reduce to Eqs. (10.13) and (10.14) and the residual image factors are seen to be contrasts (> 1) of the highest residual luminance to lowest residual luminance for each of the black and white screens.

Note: If deemed appropriate by all interested parties and provided any modifications are clearly stated in all reporting documentation:

- (1) other patterns may be used, (2) this measurement can be extended to be used with points other than at the center of the screen, and
- (3) other colors than black and white might also be important for certain applications.

10.5. Flicker

ALIAS

EIAJ flicker level, ISO flicker

DESCRIPTION

We measure intensity, *e.g.*, luminance as a function of time, then use Fourier analysis to compute modulation amplitude as a function of frequency, and finally calculate weighted modulation levels and report the frequency and weighted modulation levels. **Units:** Hz, dB Note that we have removed the word flicker for all measurements in this section as flicker is a perception that cannot be measured. Temporal Luminance Modulation (TLM) or modulation and Weighted Temporal Luminance Modulation (WTLM) or weighted modulation are used instead.

On some display technologies, certain viewing directions, test patterns, colors, and/or drive levels may cause the display to appear to flicker, even though a constant test pattern is displayed. See 4.5 Flicker Visibility Assessment for a discussion of flicker, and for a subjective flicker test that may be performed during warm-up.

SETUP

As defined by these icons, standard setup details apply (3.2).



OTHER SETUP CONDITIONS

The nominal test pattern is constant full screen white at maximum drive L_W . If other empirically or analytically derived worst-case test patterns are used, the changed color, drive level, pattern, and/or viewing angle should be listed in the report.

On some displays, the gray scale is displayed using multiple refresh frames. Use the DUT design documentation to calculate $F_{\text{repetition}}$ (normally the frame refresh rate divided by some integer), which is the gray scale image repetition frequency. $F_{\text{repetition}}$ may also be derived from manual or automatic inspection of the intensity waveform.

Intensity as a function of time may be measured with the same LMD used in 10.2.1 Temporal Response Time, with the following additional requirements (other apparatus may be used if the same results are obtained):

1. The LMD must be dark field (zero) corrected.

TABLE 10.8. Reporting (Sample Data).

Sample data only: Do not use any values shown to represent expected results of your measurements.

Residual image	
Burn-in, t	5 h
R_W	1.11
R_B	1.17
t_R	ASAP

$$R_W = \frac{\max(K_W, K_{WC})}{\min(K_W, K_{WC})} \quad (10.13)$$

$$R_B = \frac{\max(K_B, K_{BC})}{\min(K_B, K_{BC})} \quad (10.14)$$



2. The LMD must be photopically corrected unless it is known that there is no color shift as a result of temporal modulation.
3. The LMD output should be low-pass filtered, with band pass of 0 to 150 Hz (± 3 dB), and -60 dB at half the sample frequency. The filtering can be done in the LMD itself or through some external analog filter. The signal must be band limited in order to meet Nyquist criteria.

Intensity as a function of frequency is computed by Fourier analysis. The measurement procedure below assumes the use of a fast Fourier transform (FFT) on a digital computer. Other analysis procedures may be used if the same results are obtained. The sample frequency F_{sample} should be adjusted so that $N_{\text{samples}} = F_{\text{sample}} \div F_{\text{repetition}}$ is at least 64, and a power of two (64, 128, 256, ...). If F_{sample} cannot be adjusted, the intensity data should be digitally re-sampled to achieve the same effect. This sample rate restriction helps to calculate accurate modulation amplitudes by ensuring that the sub-harmonics of $F_{\text{repetition}}$ are not split between two FFT frequency range “buckets”. Other techniques may also be used as long as the same results are obtained.

TABLE 10.9. Flicker Weighting Factors		
Use linear interpolation between the listed frequencies.		
“Scaling: dB” is equivalent to “Scaling: Factor”		
Frequency (Hz)	Scaling (dB)	Scaling factor
20	0	1.00
30	-3	0.708
40	-6	0.501
50	-12	0.251
≥ 60	-40	0.010

PROCEDURE

1. Display the selected test pattern and wait until the test pattern is stable.
2. Collect the array $f_{\text{raw}}[0 \dots N_{\text{samples}} - 1]$ intensity data samples at the sample frequency F_{sample} .
3. Calculate the FFT coefficients and the corresponding modulation amplitudes. For each FFT frequency, the resulting coefficient is weighted by (multiplied by) the corresponding scaling (weighting) factor in TABLE 10.9 (right). This weighting is performed to adjust the measured modulation amplitudes to match the approximate temporal flicker sensitivity of the human eye, where flicker sensitivity decreases as the flicker frequency increases.

ANALYSIS

1. Validate the FFT algorithm as per the FFT validation section in the comments below.
2. Use $f_{\text{raw}}[]$ to calculate $f_{\text{fft}}[0 \dots (0.5N_{\text{samples}}) - 1]$, the array of FFT magnitude coefficients, each representing the modulation intensity for a certain frequency range. Note that the center frequency of $f_{\text{fft}}[n] = nF_{\text{sample}} \div N_{\text{samples}}$. Also note that $f_{\text{fft}}[0]$ is the DC, or average, intensity.
3. Scale the $f_{\text{fft}}[]$ array by the human visual sensitivity factors in TABLE 10.9, using linear interpolation between the listed values, yielding the scaled FFT coefficient array $f_{\text{sfft}}[]$.
4. For each element in $f_{\text{sfft}}[]$, calculate the modulation amplitude = $20 \log_{10}(2f_{\text{sfft}}[n] \div f_{\text{sfft}}[0])$ dB. (This is the equation for calculating dB directly from the validated FFT magnitude coefficients. If the modulation level is to be calculated from “power spectrum” FFT coefficients, where each coefficient has been squared, *either* take the square root of each coefficient to yield the validated form *or* use the alternate equation modulation level = $10 \log_{10}(\text{power}[n] \div \text{power}[0])$ dB. Here, we are calculating the weighted modulation level at each frequency in decibels with respect to the mean luminance.

REPORTING

Report any variations from standard setup/test pattern, $F_{\text{repetition}}$, F_{sample} , and the frequency and value of the largest modulation level. Optionally, report all modulation levels.

COMMENTS

This measurement is intended to be consistent with 6.10.2, “Flicker/frame response”, in IEC 61747-30-1:2012 (previously EIAJ-2522). If the LMD is photopically corrected and calibrated, the FFT coefficient array $f_{\text{fft}}[]$ is identical to the array $\text{FFT}(v)$ in B.2.2 “Fourier Coefficients” in ISO 13406-2 Annex B. Please note that the flicker weighting



factors shown are from the IEC document. *Also note that IEC 61747-30 reports flicker levels 3 dB lower than calculated in this spec due to differences in the Fourier coefficients used.* Other weighting factors may be used, as long as all interested parties agree, and the alternate factors are clearly reported in all documentation. **Warning:** Display flicker can cause discomfort, sickness, and even convulsions in susceptible individuals—see P. Wolf and R. Goosses, Relation of photosensitivity to epileptic syndromes, J. Neurol., Neurosurg., and Psychiat. 49, 1386-1391 (1986). The problem tends to be worse for frequencies near 10 Hz, for greater modulation depths, for greater angular subtense of the flicker, and for redder light. Furthermore, photosensitive seizure is now thought to affect a population 30 times as large as the light-sensitive epileptics. In response to 4 seconds of full-screen strobe on a Japanese cartoon show, 685 watchers were rushed to hospitals for seizure-symptom treatment—see M. Nomura and T. Takahashi, SID 99 Digest, pp. 338-345; M. Nomura, Neural Networks 12 (1999), 347-354. Although such flicker is incurred by video content and not by the inherent display dynamics, Nomura *et al* found they could suppress it by an adaptive filter at the display. In summary, if any display has a substantial flicker component near 10 Hz, this is cause for concern.

The FFT algorithm should return un-normalized results, with the average of the sampled values as the first term. The FFT algorithm can be validated using the following procedure:

1. Set $N_{\text{samples}} = 64$; $f_{\text{raw}}[0 \dots 47] = 100$; $f_{\text{raw}}[48 \dots 63] = 0$.
2. Perform the FFT calculation.
3. The first four resulting terms of $f_{\text{fft}}[]$ should be {75.00, 22.50, 15.94, 7.54}, or these values scaled by any constant amount. Noncompliant FFT algorithms might be corrected by replacing the first term with the average of the sampled values, or by scaling the remaining terms by a factor of two.
4. Worked Example: Use the raw data as in #1 above, and $F_{\text{repetition}} = 15$ Hz. (This might represent some hypothetical bi-level display with a 60 Hz refresh rate, using the four frame encoding (1,1,1,0) to represent 75 % full white.) The maximum flicker level for this hypothetical display is -4.4 dB at 15 Hz.

Table 10.10. Validation Data.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Index	f_{fft}	Frequency (Hz)	Weight	f_{sfft}	Flicker level (dB)
0	75	DC	1	75	N/A
1	22.5	15	1	22.5	-4.4
2	15.94	30	0.708	11.29	-10.4
3	7.54	45	0.376	2.84	-22.4

10.6. Flicker Visibility

DESCRIPTION

The purpose of this metric is to measure the visibility of flicker in displays with light output that is periodic in time. The luminance as a function of time is measured by a fast linear light measurement device over several frames. From the resulting waveform, the contrast of the fundamental frequency component is derived. That contrast is multiplied by a theoretical temporal contrast sensitivity function (TCSF) at the fundamental frequency, to yield a flicker visibility in JNDs (just noticeable differences).

SETUP

As defined by these icons, standard setup details apply (3.2).





OTHER SETUP CONDITIONS

1. The LMD must have a linear response to luminance, with zero correction.
2. The LMD must be capable of collecting samples at a rate of at least $100R$, where R is the frame rate of the display. The LMD must have a frequency response of at least 1 kHz.
3. LMD must be photopically corrected.
4. Test pattern should be full screen white at maximum drive (V_W). A smaller region can be illuminated so long as it fills the field of view of the LMD.

PROCEDURE

1. Display the test pattern.
2. Set the LMD sample rate to w_s .
3. Determine the number of frames to be collected N_f . This should be a positive integer. Larger values will produce more accurate results.
4. Determine the number of samples to be collected,

$$N_s = N_f w_s \div R_{\text{samples}}$$
5. Collect the sequence of luminance samples K_i ,
 $i = 0, N_s - 1$.
6. Compute the absolute value of the discrete Fourier transform of the sequence K_i , divided by the square root of the number of samples. Call this $|\tilde{K}_i|$. This will also be a sequence of real numbers of length N_s .
7. Locate the value $|\tilde{K}_{N_f}|$ where $i = N_f$. Note that the index i starts at zero.
8. Compute the time average luminance \bar{K} . This can be obtained as the average of the sequence K_i or from the term $|\tilde{K}_0|$ of the discrete cosine transform (DCT).
9. Compute the fundamental frequency luminance contrast $C_R = 2|\tilde{K}_{N_f}|\bar{K}^{-1}$
10. Using the value $w = w_s$ compute the estimated value of the human temporal-contrast-sensitivity function (TCSF), given by:

$$S = |\xi[(1 + 2i\pi w\tau)^{-n_1} - \zeta(1 + 2i\pi w\kappa\tau)^{-n_2}]|.$$
 In this expression $i = \sqrt{-1}$.
11. The parameters of this function are given in TABLE 10.11. A picture of the function, which can also be used to check computed values, is shown in FIGURE 10.11.
12. Compute $J = SC_R$. This is the flicker visibility in just noticeable differences (JNDs).

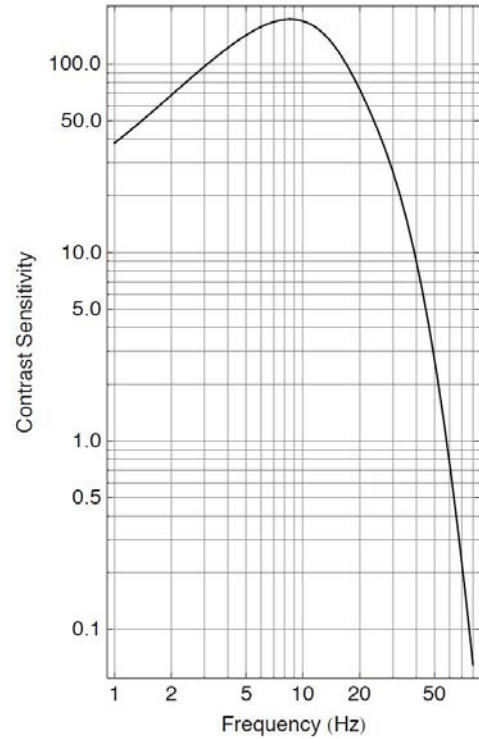


FIGURE 10.11. Graph of the temporal contrast sensitivity function (TCSF) using the standard parameters

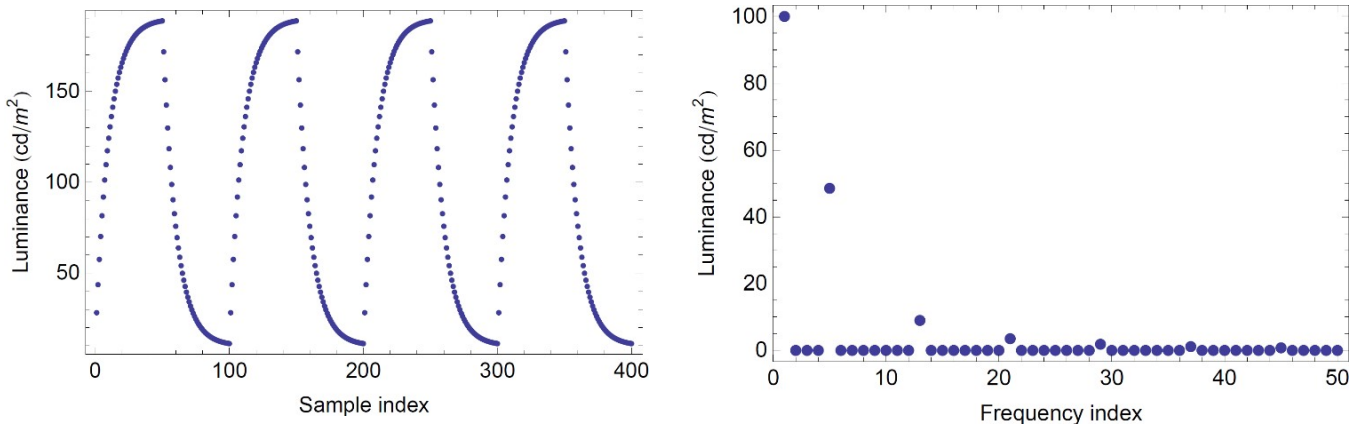


FIGURE 10.12. Waveform K_i (left) and spectrum $|\tilde{K}_i|$ (right) of an example screen flicker.

REPORTING

Report the frame rate R and the flicker visibility J_{flicker} . Only three significant figures are required.

EXAMPLE

In this example, $N_f = 4$ frames, $w_s = 6$ kHz, $R = 60$ Hz, $N_s = 400$ samples. The waveform samples are simulated by a 60 Hz square wave convolved with an exponential with time constant of 0.002 s. The mean is 100 cd m^{-2} , and the contrast is 0.9. The sampled waveform K_i is illustrated in FIGURE 10.12.

On the right in FIGURE 10.12 is shown the spectrum $|\tilde{K}_i|$. The value at 0 Hz is 100. The value at 4 cycles/sequence ($i = N_f + 1 = 5$) is 48.506. The value of the temporal contrast sensitivity function (TCSF) at $R = 50$ Hz is 2.714. The fundamental contrast is thus $2 \times 48.506 \div 100 = 0.9701$. Thus, the value of flicker visibility is $0.9701 \times 2.714 = 2.633$ JND. See TABLE 10.12.

COMMENTS

Here is more clarifying information

1. The temporal contrast sensitivity function (TCSF) is based on data of De Lange [10.2] for a 2° circular disk on a uniform background of the same time average luminance. The retinal illuminance was 1000 Td, which is approximately that obtained in a 30 year old viewing a luminance of 31.5 . It should be understood that various factors can affect the visibility of flicker. For example, flicker will be more visible for larger fields, and for higher average luminances. Other TCSF curves may be used by agreement of all interested parties.
2. This metric assumes that only the fundamental Fourier component of the display luminance modulation will be visible since higher harmonics will be at higher frequencies and have lower energy and thus be less visible. For low frame rates or exotic modulation waveforms, this assumption may be incorrect.
3. This metric is appropriate for displays with a frame rate $R \geq 10$ Hz. In a periodic luminance variation, the Fourier components will be at the fundamental $f = R$, and at higher harmonics $2f, 3f, 4f$, etc. Typically, the fundamental will have the largest amplitude. If f is at 10 Hz or above, then higher harmonics ($2f > 20$ Hz, $3f > 30$ Hz, etc.) are unlikely to be visible or to contribute to flicker visibility, due to their lower amplitude and to the rapid decline

TABLE 10.11. Parameter values for human Temporal Contrast Sensitivity Function

Parameter	Symbol	Value
Gain	ξ	148.7
Time constant (s)	τ	0.00267
Time-constant ratio	κ	1.834
Transience	ζ	0.882
Number of stages, excitation	n_1	15
Number of stages, inhibition	n_2	16

TABLE 10.12. Reporting example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Frame rate R	50	Hz
Flicker visibility, J_{flicker}	2.63	JND



in human visual sensitivity at high temporal frequencies. That is why it is sufficient to consider the fundamental alone.

4. The mathematical model of the temporal contrast sensitivity function (TCSF) is derived and explained in [10.1].
5. To validate a DFT, use as input {1, 0, 0, 0}. The output should be {.5, .5, .5, .5}.

REFERENCES

- [10.1] Watson, A. B. (1986). "Temporal Sensitivity," in K. Boff, L. Kaufman and J. Thomas (Eds.) *Handbook of Perception and Human Performance*, New York, Wiley.
- [10.2] H. de Lange Dzn, "Research into the Dynamic Nature of the Human Fovea→Cortex Systems with Intermittent and Modulated Light. II. Phase Shift in Brightness and Delay in Color Perception," *J. Opt. Soc. Am.* 48, 784-789 (1958). DOI: [10.1364/JOSA.48.000784](https://doi.org/10.1364/JOSA.48.000784)

10.7. Spatial Jitter

ALIAS

Jitter

DESCRIPTION

We measure the amplitude and frequency of variations in pixel position of the displayed image in display devices where the position of the pixel is not fixed in space (as with raster-scanned CRTs, flying-spot laser displays, etc.). We quantify the effects of perceptible time-varying distortions: jitter, swim, and drift. The perceptibility of changes in the position of an image depends upon the amplitude and frequency of the motions which can be caused by imprecise control electronics or external magnetic fields (in the case of CRTs).

Units: mm. Symbol: none.

SETUP

As defined by these icons, standard setup details apply (3.2).



OTHER SETUP CONDITIONS

Use the three-line grille patterns (see FIGURE 10.13) consisting of vertical and horizontal lines each one-pixel wide with at a gray level corresponding to white L_W (e.g., gray level 255 for an 8 bit display). Lines in test pattern must be positioned along the top, bottom, and side edges of the addressable screen, as well as within one pixel of both the vertical and horizontal centerlines (major and minor axes). Both the display and the LMD may need to sit on a vibration-damped aluminum-slab measurement bench. The motion of the test bench should be at least a factor of 10 times smaller than the jitter motion being measured.

Use a camera that has been spatially calibrated in millimeters at the measurement working distance to make the measurement. The camera frame rate should be short enough to capture jitter on the order of one display frame or less.

PROCEDURE

At each desired screen location (such as at the center and near the four corners, optionally at the centers of the edge lines) we want to measure the change in position of the center of the

line as a function of time. The measurement interval Δt must be equal to a single field period in the case of an interlaced display, or the interval Δt must be the frame period for a progressive-scan display. Tabulate horizontal

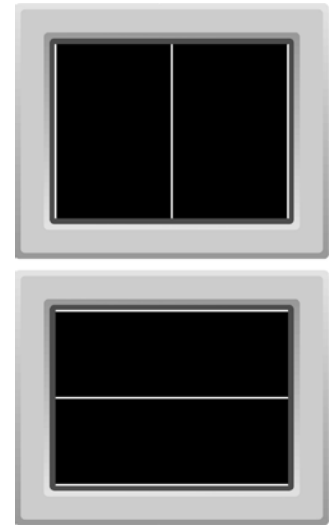


FIGURE 10.13. Test patterns for spatial jitter measurements.

TABLE 10.13. Beginning of Time Periods for Jitter, Swim and Drift in Number of frames.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Frame rate	Jitter	Swim	Drift
60 Hz	2	120	3600
72 Hz	3	144	4320
80 Hz	3	160	4800



motion as a function of time in the x -direction, $x(t)$, using the vertical-line pattern. (For raster scanned displays such as CRTs, corners typically exhibit more jitter than center screen.) Repeat for the vertical motion as a function of time in the y -direction, $y(t)$, using the horizontal-line pattern. Measure both $x(t)$ and $y(t)$ at all desired locations at times for $\Delta t_T = 150$ s (2.5 min).

ANALYSIS

Using index i to denote the position measurement at the start ($i = 0$ at $t = 0$) and at each interval Δt ($t = i\Delta t$) at any of the desired locations, the total number of measurements made on any line at each location is $N + 1$, where $N = \Delta t_T \div \Delta t$, and $i = 0, 1, 2, \dots, N$. For each measurement location, determine the shift in position for horizontal and vertical motions.

$$\delta x_i = x_{i+1} - x_i, \quad \delta y_i = y_{i+1} - y_i, \quad \text{for } i = 0, 1, 2, \dots, N, \quad (10.15)$$

Define the quantities Δx_k and Δy_k

$$\Delta x_k = \frac{1}{N-k} \sum_{n=0}^{N-k} \frac{|\delta x_n + \delta x_{n+1} + \dots + \delta x_{n+k}|}{k+1}, \quad \Delta y_k = \frac{1}{N-k} \sum_{n=0}^{N-k} \frac{|\delta y_n + \delta y_{n+1} + \dots + \delta y_{n+k}|}{k+1} \quad (10.16)$$

to denote the average amount of motion during k intervals of Δt for $k = 0, 1, 2, \dots, \Delta t_T \div \Delta t$. These window intervals $\Delta t_k = k\Delta t$ are running window averages of increasing length (see the appendix B18 Digital Filtering by Moving-Window Average for a rigorous discussion). To define the jitter, swim, and drift we identify three temporal window intervals of interest: for jitter, $0.01 \text{ s} \leq \Delta t_k < 2 \text{ s}$; for swim, $2 \text{ s} \leq \Delta t_k < 60 \text{ s}$; and for drift $60 \text{ s} \leq \Delta t_k$. Jitter, swim, and drift are the maximum average motion for those window intervals:

1. Horizontal jitter is the maximum of Δx_k for intervals $0.01 \text{ s} \leq \Delta t_k < 2 \text{ s}$ [or $(0.01 \text{ s})/\Delta t \leq k < (2 \text{ s})/\Delta t$].
2. Horizontal swim is the maximum of Δx_k for intervals $2 \text{ s} \leq \Delta t_k < 60 \text{ s}$ [or $(2 \text{ s})/\Delta t \leq k < (60 \text{ s})/\Delta t$].
3. Horizontal drift is the maximum of Δx_k for intervals $60 \text{ s} \leq \Delta t_k$ [or $(60 \text{ s})/\Delta t \leq k$].
4. Vertical jitter is the maximum of Δy_k for intervals $0.01 \text{ s} \leq \Delta t_k < 2 \text{ s}$ [or $(0.01 \text{ s})/\Delta t \leq k < (2 \text{ s})/\Delta t$].
5. Vertical swim is the maximum of Δy_k for intervals $2 \text{ s} \leq \Delta t_k < 60 \text{ s}$ [or $(2 \text{ s})/\Delta t \leq k < (60 \text{ s})/\Delta t$].
6. Vertical drift is the maximum of Δy_k for intervals $60 \text{ s} \leq \Delta t_k$ [or $(60 \text{ s})/\Delta t \leq k$].

It is sometimes useful to create a histogram for each observation position with ordinate of the average motions (Δx_k and Δy_k) vs. the k index associated with the window interval (or Δt_k).

Optionally, for multi-sync monitors measure jitter over the specified range of scanning rates. (For example, some CRT monitors running vertical scan rates other than the AC line frequency may exhibit increased jitter.) Optionally, define time periods for jitter, swim, and drift as integer multiples of the monitor's frame period, as shown for examples in the table.

Measure and report instrumentation motion by viewing a Ronchi ruling or illuminated razor edge mounted to the top of the display, for example. It may be necessary to mount both the optics and the monitor on a vibration damped surface to reduce vibrations.



TABLE 10.14. Sample Data for Scan Jitter, Maximum Motions.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Report:	Jitter/Swim/Drift:			$\leq 0.251\text{ mm}$		
<i>Motions (in mm) at maximum luminance of white lines on black; Time scales: $0.01\text{ s} \leq \text{Jitter} < 2\text{ s} \leq \text{Swim} < 60\text{ s} \leq \text{Drift}$</i>						
<i>Instrumental motions less than 0.003 mm.</i>						
Screen	Vertical Motion			Horizontal Motion		
Position	Jitter	Swim	Drift	Jitter	Swim	Drift
Center	0.089	0.097	0.102	0.030	0.033	0.033
Upper Right	0.127	0.140	0.157	0.104	0.124	0.124
Lower Right	0.130	0.160	0.163	0.203	0.244	0.251
Lower Left	0.109	0.127	0.137	0.147	0.191	0.191

REPORTING

Report the maximum jitter/swim/drift measured.

COMMENTS

Motions are most noticeable below 5 Hz and are perceived as degraded focus above 25 Hz. The required measurement locations can be negotiated beyond the five (center and corner) locations used in this procedure.



10.8. Color Residual Image Methods

NOTE: This measurement can cause irreparable damage to the display.

ALIAS

burn-in, image retention, image sticking

DESCRIPTION

Measure the residual image of a high-contrast checkerboard.

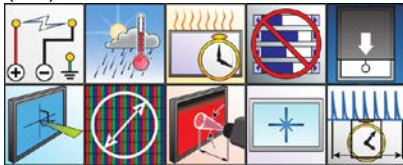
Units: None, results are contrasts.

Symbol: R_W for white, R_R for red, R_G for green, R_B for blue

This is a measurement of how the screen is affected by a 5×5 color checkerboard stress pattern in FIGURE 10.14. Initially, we will measure a test pattern (with white, red, green, and blue patch of 25 %, 50 %, or 75 % signal level) at 12 locations to account for any luminance non-uniformities (FIGURE 10.15). Then we burn in the display using the 5×5 checkerboard (moving) stress pattern (Fig. 3). Finally, we examine the same initial test pattern (Fig. 2) at 12 locations to see if there is any residual image. The actual measurements are contained in the next two sections, one for short-term retention and one for long-term retention.

SETUP

As defined by these icons, standard setup details apply (3.2):



OTHER SETUP CONDITIONS

Test pattern (with white, red, green and blue patch of 25 %, 50 %, or 75 % signal level), and 5×5 color checkerboard (moving) stress pattern. Arrange to measure the display at 12 locations of test pattern. Depending upon how uniform the screen is, it may be necessary to measure at the exact same 3 locations for each color throughout the procedure. You will need to display a test pattern (with white, red, green and blue patch of 25 %, 50 %, or 75 % signal level), and a 5×5 color checkerboard (moving) stress pattern.

TABLE 10.15 lists the pixel values to measure residual image on SDR mode, as 8-bit limited or full range.

TABLE 10.16 lists the pixel values to measure residual image in HDR mode, as 10-bit limited or full range values.

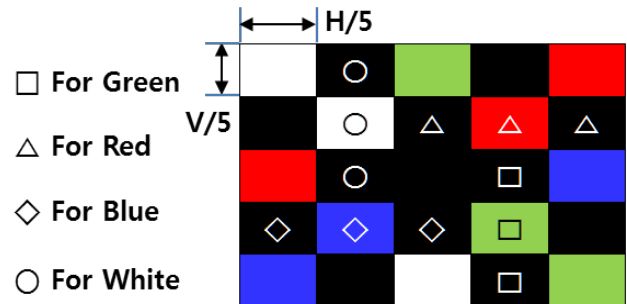


FIGURE 10.14. Measurement locations and box size

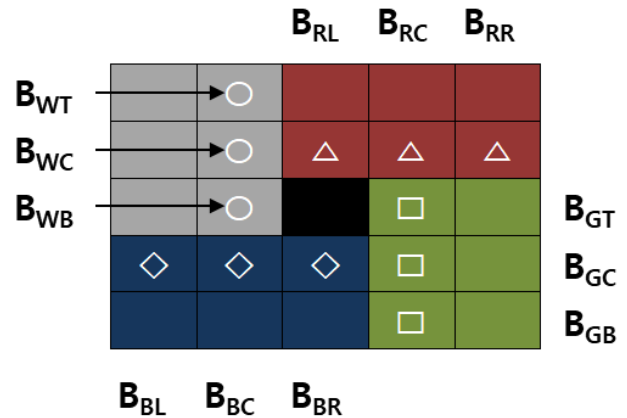


FIGURE 10.15. Initial measuring points in test pattern



5 X 5 color checkerboard stress pattern
The R/G/B/W part of the center section is fixed, and the color patch part of the fixed outline is rotated to prevent screen burn-in prevention function.

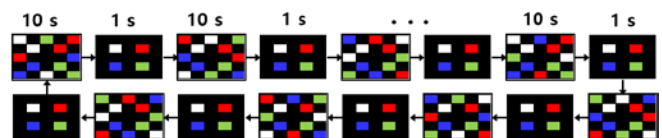


FIGURE 10.16. Burn-in procedure.



TABLE 10.15. SDR 8-bit cases.

Range	Limited			Full		
Signal level	25 %	50 %	75 %	25 %	50 %	75 %
Red	(71, 0,0)	(126, 0,0)	(181, 0,0)	(64, 0,0)	(128, 0,0)	(192, 0,0)
Green	(0, 71,0)	(0,126,0)	(0,181,0)	(0,64,0)	(0,128,0)	(0,192,0)
Blue	(0,0,71)	(0,0,126)	(0,0,181)	(0,0,64)	(0,0,128)	(0,0,191)
Gray	(71,71,71)	(126,126,126)	(181,181,181)	(64,64,64)	(128,128,128)	(192,192,192)
Black	(16,16,16)			(0,0,0)		
White	(235,235,235)			(255,255,255)		

TABLE 10.16. SDR 10-bit cases.

Range	Limited			Full		
Signal level	25 %	50 %	75 %	25 %	50 %	75 %
Red	(283, 0 ,0)	(502, 0 ,0)	(722, 0 ,0)	(256, 0 ,0)	(512, 0 ,0)	(768, 0 ,0)
Green	(0, 283, 0)	(0, 502, 0)	(0, 722, 0)	(0, 256, 0)	(0, 512, 0)	(0, 768, 0)
Blue	(0, 0, 283)	(0, 0, 502)	(0, 0, 722)	(0, 0, 256)	(0, 0, 512)	(0, 0, 768)
Gray	(283, 283, 283)	(502, 502, 502)	(722, 722, 722)	(256, 256, 256)	(512, 512, 512)	(768, 768, 768)
Black	(64, 64, 64)			(0, 0, 0)		
White	(940, 940, 940)			(1023, 1023, 1023)		

For HDR, the SMPTE ST 2084 (PQ) EOTF is used and, as a guidance, the metadata below would be sent to the DUT:

Mastering display peak white luminance	1,000 cd m ⁻²
Mastering display black luminance	0 cd m ⁻²
Mastering display colorimetry	Rec. ITU-R BT.2020
Mastering display white point	D65

Note: If deemed appropriate by all interested parties and provided any modifications are clearly stated in all reporting documentation: (1) other patterns may be used, (2) this measurement can be extended to be used with points other than at the 12 locations, and (3) other colors than white, red, green and blue might also be important for certain applications.

10.8.1 Color Short-Term Image Retention

NOTE: This measurement can cause irreparable damage to the display.

ALIAS

image retention, image sticking

DESCRIPTION

Measure the residual image of a high-contrast checkerboard.

Units: None, results are contrasts.

Symbol: R_{SW} for white, R_{SR} for red, R_{SG} for green, R_{SB} for blue

This measurement applies the previous method for color image retention to the measurement of short-term retention or sticking. Short-term retention effects may fade with time and must be captured quickly.

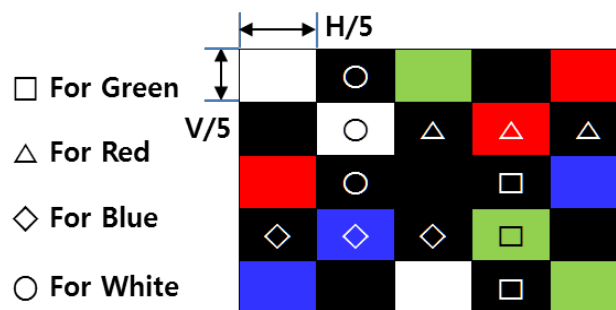


FIGURE 10.17. Measurement locations and box size



SETUP

As defined by these icons, standard setup details apply (3.2):



OTHER SETUP CONDITIONS

Use of a video photometer or other high-speed light measuring device is recommended in order to capture the transient effect of short-term image retention. In this measurement no attempt at recovery is applied between the burn-in and the final measurement.

PROCEDURE

1. **Aging:** To warm up all sub-pixels, sequential R/G/B/W patterns should be applied for more than 30 min as shown in FIGURE 10.18.
 2. **Initial measurements:** Display a test pattern (with white, red, green, and blue patch of 25 % (or 50 %, or 75 %) signal level and measure the center luminance B_{XC} the luminance on each side of center B_{XR} and B_{XL} (for right and left) for red or blue patch. Similarly, measure the center luminance B_{XC} the luminance on each side of center B_{XT} and B_{XB} (for top and bottom) for white or green patch as shown in FIGURE 10.19:
- B_{WT} , B_{WC} , and B_{WB} for white,
 B_{RL} , B_{RC} , and B_{RR} for red,
 B_{GT} , B_{GC} , and B_{GB} for green,
 B_{BL} , B_{BC} , and B_{BR} for blue
3. **Burn-in:** Burn in the 5×5 color checkerboard (sequential) stress pattern as shown in FIGURE 10.20 by allowing it to remain displayed continuously for a certain burn-in time t agreed to by all interested parties. Near the end of the burn-in time t align the LMD to measure at the same 12 locations measured in initial measurements.
 4. **Short-Term Measurement:** At the end of the burn-in time t , switch the DUT directly from a 5×5 color checkerboard (moving) stress pattern to the initial test pattern. Allow approximately a 1 second recovery time after the pattern change before making measurements. *If less than 1 second recovery time is desired, then careful attention needs to be given to triggering the acquisition.* Integration time for the measurements

Aging with R/G/B/W patterns to warm up all sub-pixels.

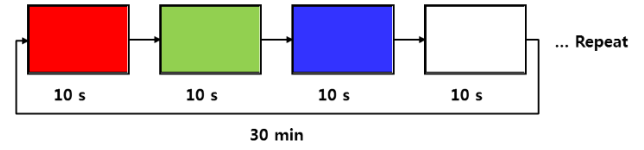


FIGURE 10.18. Spatial uniform aging procedure

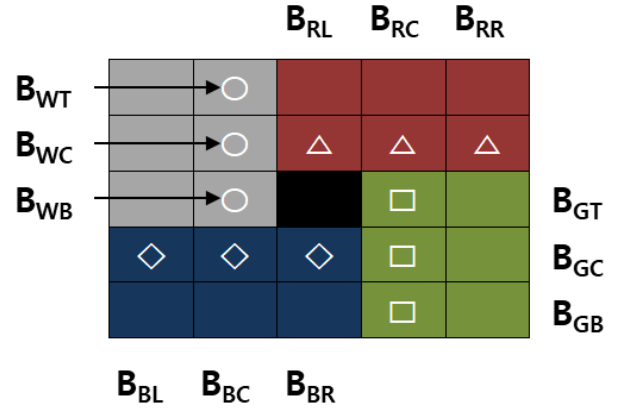


FIGURE 10.19. Initial measuring points in test pattern



5 X 5 color checkerboard stress pattern
 The R/G/B/W part of the center section is fixed, and the color patch part of the fixed outline is rotated to prevent screen burn-in prevention function.

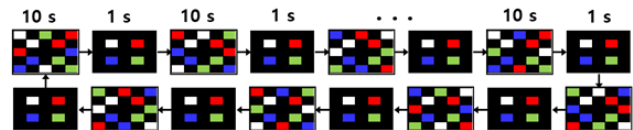


FIGURE 10.20. Burn-in procedure.

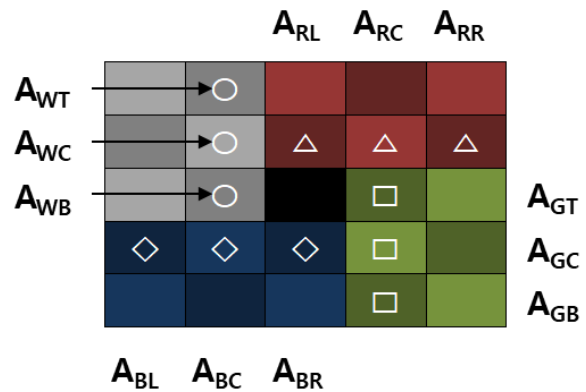


FIGURE 10.21. Short-term measuring points in test pattern.



should be less than 1-2 seconds. Measure luminance at the measuring points as shown in FIGURE 10.21. Measure the center luminance A_{XC} , the luminance on each side of center A_{XR} and A_{XL} (for right and left) for red or blue patch. Similarly, measure the center luminance A_{XC} the luminance on each side of center A_{XT} and A_{XB} (for top and bottom) for white or green patch. These measurements should be made in as small a time as is possible.

A_{WT} , A_{WC} , and A_{WB} for white,

A_{RL} , A_{RC} , and A_{RR} for red,

A_{GT} , A_{GC} , and A_{GB} for green,

A_{BL} , A_{BC} , and A_{BR} for blue

5. **Transient Measurement:** Following the short-term measurement a recovery procedure can be applied to the display and the final measurement repeated (see method 10.8.2 Long-Term Image retention) to determine if the image retention is transient in nature.

ANALYSIS

In what follows, we will be using ratios of these luminance values to obtain contrasts. By using ratios, we eliminate the effects of overall luminance degradation of the display from either an extended warm-up period or from spatial uniform aging. We also need to account for any non-uniformity inherent in the screen for the 12 measurement points. (See 10.4 Comments, for a more detailed explanation.) The residual image factors are defined as follows:

Short-Term Residual Image Factors:

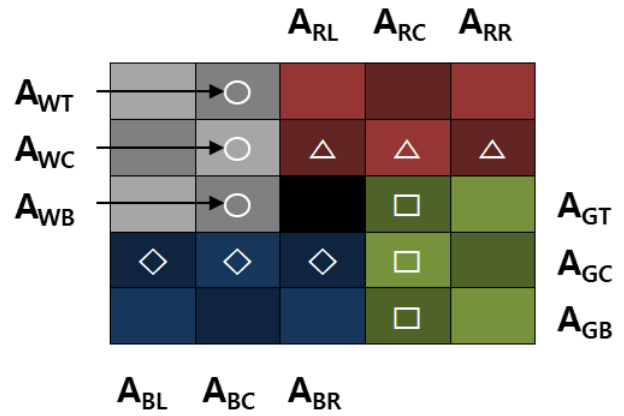


FIGURE 10.22. Short-term measuring points in test pattern

$$\begin{aligned}
 R_{SW} &= \frac{\max[(B_{WB} + B_{WT}) \times A_{WC}, (A_{WB} + A_{WT}) \times B_{WC}]}{\min[(B_{WB} + B_{WT}) \times A_{WC}, (A_{WB} + A_{WT}) \times B_{WC}]} \\
 R_{SR} &= \frac{\max[(B_{RL} + B_{RR}) \times A_{RC}, (A_{RL} + A_{RR}) \times B_{RC}]}{\min[(B_{RL} + B_{RR}) \times A_{RC}, (A_{RL} + A_{RR}) \times B_{RC}]} \\
 R_{SG} &= \frac{\max[(B_{GB} + B_{GT}) \times A_{GC}, (A_{GB} + A_{GT}) \times B_{GC}]}{\min[(B_{GB} + B_{GT}) \times A_{GC}, (A_{GB} + A_{GT}) \times B_{GC}]} \\
 R_{SB} &= \frac{\max[(B_{BL} + B_{BR}) \times A_{BC}, (A_{BL} + A_{BR}) \times B_{BC}]}{\min[(B_{BL} + B_{BR}) \times A_{BC}, (A_{BL} + A_{BR}) \times B_{BC}]}
 \end{aligned} \tag{10.17}$$

The above equations take into account compensation for non-uniformities inherent in the screen for the 12 measurement points. R_{SW} is the contrast of the short-term residual image for the white, R_{SR} is the contrast of the short-term residual image for the red, R_{SG} is the contrast of the short-term residual image for the green, and R_{SB} is the contrast of the short-term residual image for the blue.

REPORTING

Report the burn-in time t (the agreed upon time interval, in the example we show 10 min), recovery time (t_R), measurement integration time, and the measured instantaneous residual image contrasts of red R_{SR} , green R_{SG} , blue R_{SB} , and white R_{SW} , and if long-term measurements were performed to determine the transient nature of the retention,



report the, the recovery time (t_R), recovery procedures and long-term residual image contrasts of red R_{LR} , green R_{LG} , blue R_{LB} , and white R_{LW} to no more than three significant figures.

COMMENTS

1. Fast measurement is very important because there are many points to be measured. Therefore, it is strongly recommended to finish the measurement within a short time by using a 2D LMD instead of a point LMD.
2. This measurement is based on RGB primary color display. If a display has non RGB primary colors, then its own primary colors such as CMY or RGBY could be used to make a 5×5 color checkboard (moving) stress pattern or test pattern. It is ideal to use a pattern with all the subpixel primary colors to stress uniformly to test every color (sub) pixel.
3. Testing additional signal levels of 50 % and 75 % should be done by repeating the entire procedure from steps 1 to 5.

Table 10.17. Short-term residual image factors.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Signal level		25%		Signal level		50%		Signal level		75%	
Qty	Value	Qty	Value	Qty	Value	Qty	Value	Qty	Value	Qty	Value
B_{WT}	13.19	A_{WT}	12.75	B_{WT}	114.67	A_{WT}	112.77	B_{WT}	167.70	A_{WT}	168.01
B_{WC}	14.00	A_{WC}	13.86	B_{WC}	119.70	A_{WC}	117.95	B_{WC}	176.24	A_{WC}	174.46
B_{WB}	14.36	A_{WB}	13.90	B_{WB}	122.84	A_{WB}	120.52	B_{WB}	180.35	A_{WB}	178.72
B_{RL}	5.32	A_{RL}	5.11	B_{RL}	45.99	A_{RL}	44.31	B_{RL}	43.37	A_{RL}	41.55
B_{RC}	5.34	A_{RC}	5.42	B_{RC}	46.41	A_{RC}	44.83	B_{RC}	43.28	A_{RC}	42.00
B_{RR}	5.74	A_{RR}	5.53	B_{RR}	47.91	A_{RR}	45.63	B_{RR}	45.62	A_{RR}	44.41
B_{GT}	10.65	A_{GT}	11.05	B_{GT}	104.79	A_{GT}	105.08	B_{GT}	125.20	A_{GT}	126.09
B_{GC}	10.82	A_{GC}	11.31	B_{GC}	108.36	A_{GC}	111.12	B_{GC}	130.24	A_{GC}	131.62
B_{GB}	10.33	A_{GB}	10.27	B_{GB}	109.39	A_{GB}	109.98	B_{GB}	131.01	A_{GB}	130.83
B_{BL}	1.98	A_{BL}	2.08	B_{BL}	15.48	A_{BL}	15.65	B_{BL}	17.53	A_{BL}	17.46
B_{BC}	2.00	A_{BC}	2.18	B_{BC}	15.99	A_{BC}	16.27	B_{BC}	17.85	A_{BC}	18.10
B_{BR}	2.06	A_{BR}	2.17	B_{BR}	16.21	A_{BR}	16.23	B_{BR}	18.29	A_{BR}	18.34
burn-in time t		10 min									
Recovery Procedures		None									
recovery time t_R		1 s									
R_{SW}	1.023				1.003				1.006		
R_{SG}	1.029				1.021				1.008		
R_{SR}	1.054				1.008				1.005		
R_{SB}	1.037				1.011				1.014		
Recovery Procedures		Alternating Full Screen Red, Green, Blue, White at 100% stimulus, 10 seconds per frame, 10 minutes total duration.									
Recovery time t_R		10 minutes									
R_{LW}	1.016				1.002				1.005		
R_{LG}	1.020				1.015				1.006		
R_{LR}	1.038				1.006				1.003		
R_{LB}	1.026				1.008				1.010		



10.8.2 Color Long-Term Image Retention

NOTE: This measurement can cause irreparable damage to the display.

ALIAS

image retention, image sticking

DESCRIPTION

Measure the residual image of a high-contrast checkerboard.

Units: None, results are contrasts.

Symbol: R_{LW} for white, R_{LR} for red, R_{LG} for green, R_{LB} for blue

This measurement applies the previous method for color image retention to the measurement of long-term retention or burn-in.

SETUP

As defined by these icons, standard setup details apply (3.2):



OTHER SETUP CONDITIONS

A spot photometer may be used for this measurement, as high-speed is not required.

PROCEDURE

- Aging:** To warm up all sub-pixels, sequential R/G/B/W patterns should be applied for more than 30 min as shown in FIGURE 10.24.
- Initial measurements:** Display a test pattern (with white, red, green, and blue patch of 25 % (or 50 %, or 75 %) signal level and measure the center luminance B_{XC} the luminance on each side of center B_{XR} and B_{XL} (for right and left) for red or blue patch. Similarly, measure the center luminance B_{XC} the luminance on each side of center B_{XT} and B_{XB} (for top and bottom) for white or green patch as shown in FIGURE 10.25: B_{WT} , B_{WC} , and B_{WB} for white, B_{RL} , B_{RC} , and B_{RR} for red, B_{GT} , B_{GC} , and B_{GB} for green, B_{BL} , B_{BC} , and B_{BR} for blue
- Burn-in:** Burn in the 5×5 color checkerboard (sequential) stress pattern as shown in FIGURE 10.26 by allowing it to remain displayed continuously for a certain burn-in time t agreed to by all interested parties.

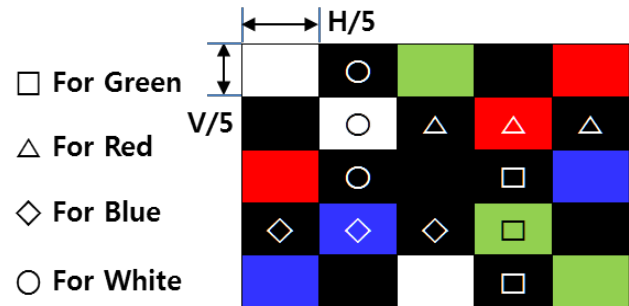


FIGURE 10.23. Measurement locations and box size

Aging with R/G/B/W patterns to warm up all sub-pixels.

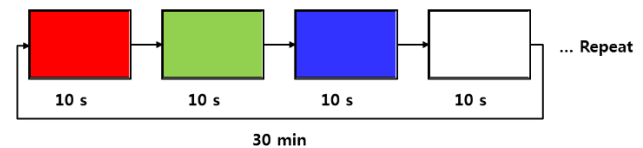


FIGURE 10.24. Spatial uniform aging procedure

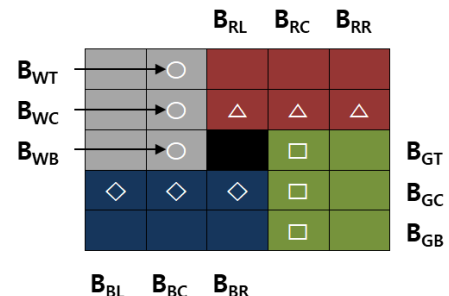


FIGURE 10.25. Initial measuring points in test pattern



5 X 5 color checkerboard stress pattern
The R/G/B/W part of the center section is fixed, and the color patch part of the fixed outline is rotated to prevent screen burn-in prevention function.

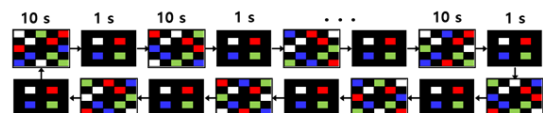


FIGURE 10.26. Burn-in procedure.



Near the end of the burn-in time t align the LMD to measure at the same 12 locations measured in initial measurements.

4. **Recovery:** There is no set way to recover from a residual image. For example, recovery procedures could include:
 - a. Displaying video content (or random patterns simulating video content)
 - b. Maintaining a full-screen white for a period of time
 - c. Maintaining full screen black for a period of time
 - d. Displaying a changing series of images
 - e. Displaying the inverse of the image that originally produce the residual image
 - f. Display specific integrated functions

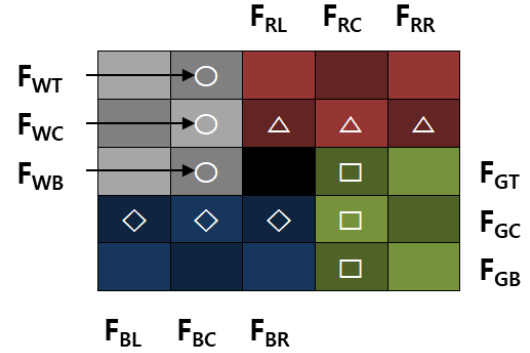


FIGURE 10.27. Long-term measuring points in test pattern.

DUT Manufacturer should be contacted for information on any preferred recovery technique. Any recovery procedure used must be easily repeatable; functions or procedures only available to DUT manufacturer engineers may not be used. The recovery time t_R and recovery procedure should be reported

5. **Long-term measurement:** Following burn-in, the DUT shall then be run through a recovery procedure agreed by all interested parties, ideally in consultation with the DUT manufacturer. At the end of the recovery procedure, switch the DUT directly to the initial test pattern. As before, measure luminance at the measuring points as shown in FIGURE 10.27. Measure the center luminance F_{XC} , the luminance on each side of center F_{XR} and F_{XL} (for right and left) for red or blue patch. Similarly, measure the center luminance F_{XC} the luminance on each side of center F_{XT} and F_{XB} (for top and bottom) for white or green patch.
 F_{WT} , F_{WC} , and F_{WB} for white,
 F_{RL} , F_{RC} , and F_{RR} for red,
 F_{GT} , F_{GC} , and F_{GB} for green,
 F_{BL} , F_{BC} , and F_{BR} for blue

ANALYSIS

In what follows, we will be using ratios of these luminance values to obtain contrasts. By using ratios, we eliminate the effects of overall luminance degradation of the display from either an extended warm-up period or from spatial uniform aging. We also need to account for any non-uniformity inherent in the screen for the 12 measurement points. The residual image factors are defined as follows:

Long-Term residual image factors:

$$\begin{aligned}
 R_{LW} &= \frac{\max[(F_{WB} + F_{WT}) \times B_{WC}, (B_{WB} + B_{WT}) \times F_{WC}]}{\min[(F_{WB} + F_{WT}) \times B_{WC}, (B_{WB} + B_{WT}) \times F_{WC}]} \\
 R_{LR} &= \frac{\max[(F_{RL} + F_{RR}) \times B_{RC}, (B_{RL} + B_{RR}) \times F_{RC}]}{\min[(F_{RL} + F_{RR}) \times B_{RC}, (B_{RL} + B_{RR}) \times F_{RC}]} \\
 R_{LG} &= \frac{\max[(F_{GB} + F_{GT}) \times B_{GC}, (B_{GB} + B_{GT}) \times F_{GC}]}{\min[(F_{GB} + F_{GT}) \times B_{GC}, (B_{GB} + B_{GT}) \times F_{GC}]}
 \end{aligned} \tag{10.18}$$



$$R_{LB} = \frac{\max[(F_{BL} + F_{BR}) \times B_{BC}, (B_{BL} + B_{BR}) \times F_{BC}]}{\min[(F_{BL} + F_{BR}) \times B_{BC}, (B_{BL} + B_{BR}) \times F_{BC}]}$$

The above equations take into account compensation for non-uniformities inherent in the screen for the 12 measurement points (see 10.4 Comments, for a more detailed explanation.)

R_{LW} is the contrast of the long-term residual image for the white, R_{LR} is the contrast of the long-term residual image for the red, R_{LG} is the contrast of the long-term residual image for the green, and R_{LB} is the contrast of the long-term residual image for the blue.

REPORTING

Report the burn-in time t (the agreed upon time interval, in the example we show 400 hours), the recovery time (t_R), recovery procedures, and the long-term residual image contrasts of red R_{LR} , green R_{LG} , blue R_{LB} , and white R_{LW} to no more than three significant figures.

COMMENTS

This measurement is based on RGB primary color display. If a display has non-RGB primary colors, then its own primary colors such as CMY or RGBY could be used to make a 5×5 color checkboard (moving) stress pattern or test pattern. It is ideal to use a pattern with all the subpixel colors to stress uniformly to test every color (sub) pixel.

Table 10.18. Long-term residual image factors.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Signal level		25%		Signal level		50%		Signal level		75%	
Qty	Value	Qty	Value	Qty	Value	Qty	Value	Qty	Value	Qty	Value
B_{WT}	6.87	F_{WT}	6.71	B_{WT}	110.80	F_{WT}	108.28	B_{WT}	450.10	F_{WT}	438.82
B_{WC}	7.00	F_{WC}	6.47	B_{WC}	117.00	F_{WC}	106.74	B_{WC}	453.50	F_{WC}	442.73
B_{WB}	7.17	F_{WB}	6.71	B_{WB}	111.70	F_{WB}	108.65	B_{WB}	457.60	F_{WB}	445.87
B_{RL}	2.11	F_{RL}	2.24	B_{RL}	35.45	F_{RL}	36.77	B_{RL}	89.80	F_{RL}	94.45
B_{RC}	2.14	F_{RC}	1.79	B_{RC}	31.50	F_{RC}	30.73	B_{RC}	82.95	F_{RC}	77.26
B_{RR}	2.23	F_{RR}	2.39	B_{RR}	29.16	F_{RR}	34.68	B_{RR}	78.08	F_{RR}	85.61
B_{GT}	3.17	F_{GT}	3.10	B_{GT}	56.86	F_{GT}	61.35	B_{GT}	274.90	F_{GT}	256.17
B_{GC}	3.11	F_{GC}	2.95	B_{GC}	60.95	F_{GC}	52.83	B_{GC}	252.90	F_{GC}	223.43
B_{GB}	3.16	F_{GB}	3.18	B_{GB}	53.56	F_{GB}	50.63	B_{GB}	219.80	F_{GB}	209.24
B_{BL}	0.46	F_{BL}	0.45	B_{BL}	8.62	F_{BL}	8.21	B_{BL}	36.76	F_{BL}	36.59
B_{BC}	0.46	F_{BC}	0.41	B_{BC}	8.72	F_{BC}	8.04	B_{BC}	36.28	F_{BC}	34.45
B_{BR}	0.46	F_{BR}	0.47	B_{BR}	8.45	F_{BR}	8.41	B_{BR}	35.14	F_{BR}	35.28
Burn-in time t		400 hours									
Recovery Procedures		1. Power off for 24 hours 2. Activate Pixel Refresher function (in manufacture guide) for 1 hour									
Recovery time t_R		25 hours (24 hours for power off and 1 hour for Pixel Refresher function)									
R_{LW}		1.034				1.069				1.002	
R_{LR}		1.044				1.170				1.065	
R_{LG}		1.274				1.170				1.152	
R_{LB}		1.132				1.056				1.053	



10.9. Video-Based Image Retention

NOTE: This measurement can cause irreparable damage to the display.

ALIASES

latent image, burn-in, image sticking, residual image

DESCRIPTION

This method is not intended to detect image retention resulting from fixed patterns or static contents. Some applications, such as gaming, public information displays, arrival/departure info, GPS tools as used by rideshare drivers, and others, may contain fixed images used for extended periods of time. For those applications, the method described in section 10.8 may be more appropriate. Measure the image retention of a contrast checkerboard. **Units:** None, results are contrast ratios. **Symbols:** R_W for white, R_R , R_G , R_B for color.

In this section, image retention is measured for the case of display stress applied by video-based test images. To account for any existing luminance non-uniformities, initial test patterns consisting of white, red, green, and blue are first measured. Then a stress pattern is applied and finally, the initial test pattern is applied, and the display is measured again to see if there is any image retention. This method also can be used for comparison of image retention protection methods between displays based on video content.

APPLICATION

This method applies to any display primarily used for displaying video content.

SETUP

As defined by these icons, standard setup details apply (3.2):



OTHER SETUP CONDITIONS

Designate locations on the test patterns for the initial/final measurements. A video sample agreed by all parties is selected as a stress pattern. In deciding contents to use as stress patterns, please see COMMENTS (1). Calculate the code values of an accumulated image for red, green, blue, and white of the agreed video:

$$V_Q(x, y) = \frac{1}{N} \sum_{n=1}^N V'_Q(x, y, n) \quad (10.19)$$

where $V_Q(x, y)$ are code values of accumulated images for color Q by Eq.(10.9) above, $V'_Q(x, y, n)$ are code values for color Q of pixel (x, y) of frame n and N is the number of frames. Next, calculate the maximum, average, and the minimum of the frame-averaged RGB levels:

$$V_{Q\min} = \min_{x=1\dots X, y=1\dots Y} V_Q(x, y) \quad (10.20)$$

$$V_{Q\text{ave}} = \frac{1}{XY} \sum_{x=1}^X \sum_{y=1}^Y V_Q(x, y) \quad (10.21)$$

$$V_{Q\max} = \max_{x=1\dots X, y=1\dots Y} V_Q(x, y) \quad (10.22)$$

$$V_{W\min} = \frac{1}{3} (V_{R\min} + V_{G\min} + V_{B\min}) \quad (10.23)$$



$$V_{Wave} = \frac{1}{3}(V_{Rave} + V_{Gave} + V_{Bave}) \quad (10.24)$$

$$V_{Wmax} = \frac{1}{3}(V_{Rmax} + V_{Gmax} + V_{Bmax}) \quad (10.25)$$

where V_{Qmin} , V_{Qave} and V_{Qmax} are the minimum, average, and maximum code values by above Eq.(10.20) to (10.25) in accumulated image, respectively. X and Y is the number of horizontal and vertical pixels, respectively. The levels of V, V' in Eq.(10.19) to (10.25) are between 0 and $2^k - 1$, where k is the signal quantization (bit depth), e.g., 0...255 in the case of 8 bits. The bit depth can be changed depending on the type of video sample. If the bit depth of video sample is 10 bits, k would be 10.

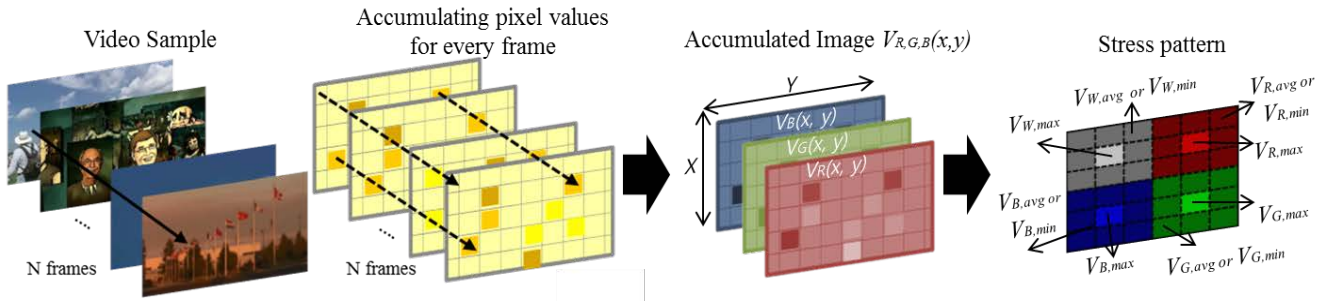


FIGURE 10.28. Procedure to extract the minimum, average, and maximum signal level for color R, G, and B, respectively.

PROCEDURE

1. **Warm up:** Sequentially display full-screen R, G, B and W test patterns as shown in FIGURE 10.29, each for 10 seconds for a total of 30 minutes.
2. **Initial Measurements:** Display the initial test pattern (with white, red, green, and blue patches of 100% signal level) as shown in FIGURE 10.30 and measure the luminance values at the designated locations (center, up, down, right, left). (For instance, in white case, L_{WC} , L_{WU} , L_{WD} , L_{WR} , L_{WL}).
3. **Stress:** Apply the stress pattern based on V_{Qmin} and V_{Qavg} or V_{Qmax} as shown in FIGURE 10.31 allowing it to remain displayed continuously for a duration of T hours, as agreed by the parties. TABLE 10.19 to TABLE 10.21 show code values for the test pattern based on example video samples. Stress pattern is configured following "Stress pattern for Time T " in FIGURE 10.31.

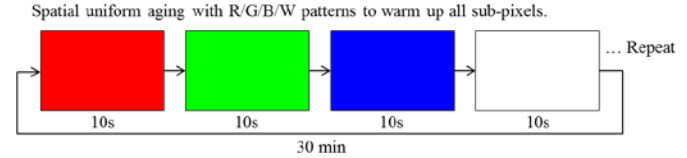


FIGURE 10.29. Spatial uniform aging procedure.

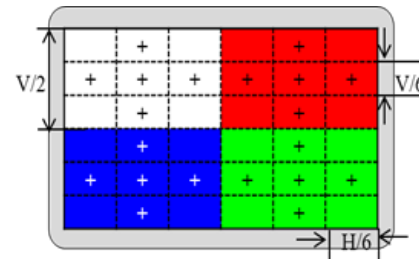


FIGURE 10.30. Measurement locations and box size

This is an alternating or blinking pattern to avoid any recognition algorithm for still patterns. In addition, the calculation procedure of code values for stress pattern as shown in FIGURE 10.28, is described by Eqs.(10.19) to (10.25).

4. **Recovery:** The manufacturer should be contacted for any information on any preferred recovery technique. Any recovery procedure used must be easily repeatable; functions or procedures only available to DUT manufacturer engineers may not be used. The recovery time t_R and recovery procedure shall be reported. Turn off the display and



stabilize it to the standard operation condition. Then turn on the display again. Also set all power supplies to standard operation conditions. Before the final measurement, apply the R, G, B, W sequence of step 1.

5. **Final Measurements:** The final measurement is performed under the same conditions as the initial measurement. At the end of the recovery period, switch the DUT from R, G, B and W sequence pattern to the test pattern for final measurement, measure the luminance values at the designated locations (center, up, down, right, left); for the case of white, K_{WC} , K_{WU} , K_{WD} , K_{WR} , K_{WL}).

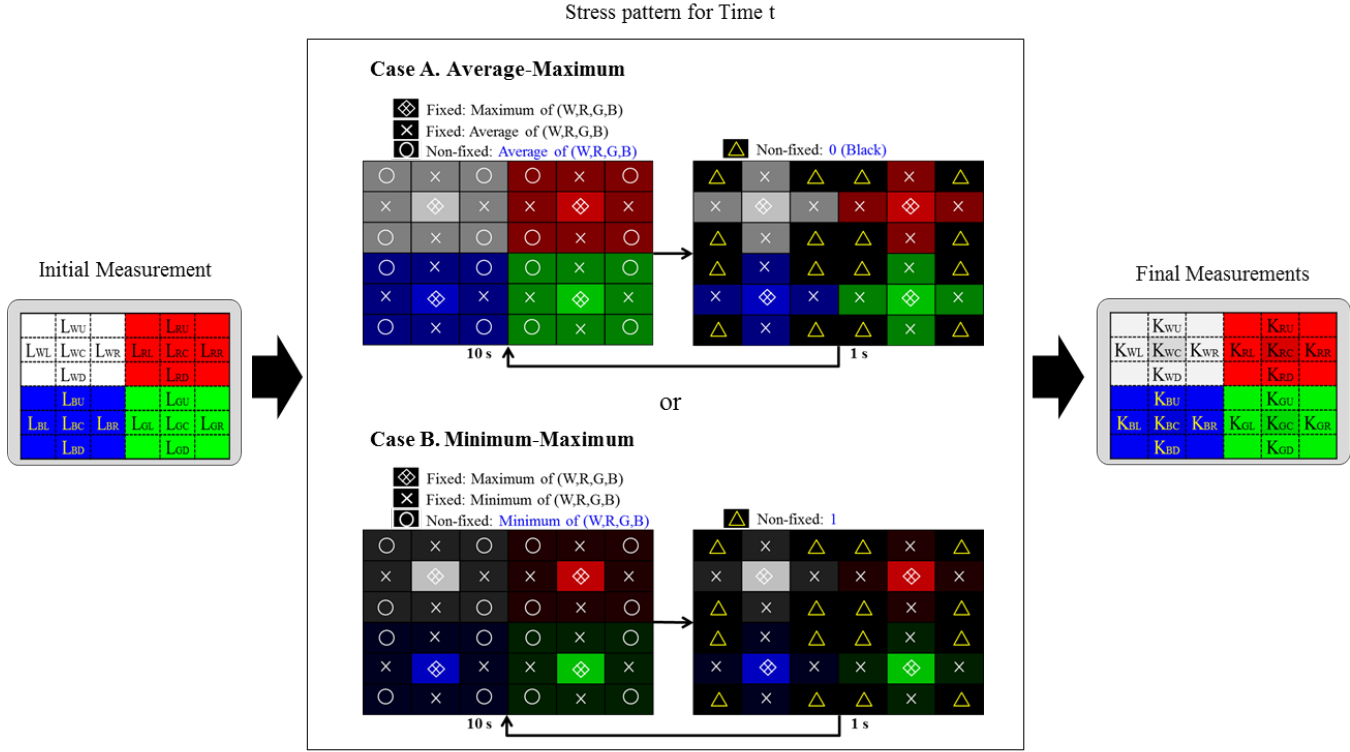


FIGURE 10.31. Procedure of video-based image retention

ANALYSIS

In what follows, we will be using ratios of these luminance values to obtain the luminous contrast. By using ratios, we eliminate the effects of overall luminance degradation of the display from either an extended warm-up period or from spatial uniform aging. Any non-uniformity inherent in the screen for the four measurement locations is also accounted for. The *image retention factors* are defined by Eqs. (10.26) to (10.29) below.

$$R_W = \frac{\max[(K_{WR} + K_{WL} + K_{WU} + K_{WD})L_{WC}, (L_{WR} + L_{WL} + L_{WU} + L_{WD})K_{WC}]}{\min[(K_{WR} + K_{WL} + K_{WU} + K_{WD})L_{WC}, (L_{WR} + L_{WL} + L_{WU} + L_{WD})K_{WC}]} \quad (10.26)$$

$$R_R = \frac{\max[(K_{RR} + K_{RL} + K_{RU} + K_{RD})L_{RC}, (L_{RR} + L_{RL} + L_{RU} + L_{RD})K_{RC}]}{\min[(K_{RR} + K_{RL} + K_{RU} + K_{RD})L_{RC}, (L_{RR} + L_{RL} + L_{RU} + L_{RD})K_{RC}]} \quad (10.27)$$

$$R_G = \frac{\max[(K_{GR} + K_{GL} + K_{GU} + K_{GD})L_{GC}, (L_{GR} + L_{GL} + L_{GU} + L_{GD})K_{GC}]}{\min[(K_{GR} + K_{GL} + K_{GU} + K_{GD})L_{GC}, (L_{GR} + L_{GL} + L_{GU} + L_{GD})K_{GC}]} \quad (10.28)$$



$$R_B = \frac{\max [(K_{BR} + K_{BL} + K_{BU} + K_{BD})L_{BC}, (L_{BR} + L_{BL} + L_{BU} + L_{BD})K_{BC}]}{\min [(K_{BR} + K_{BL} + K_{BU} + K_{BD})L_{BC}, (L_{BR} + L_{BL} + L_{BU} + L_{BD})K_{BC}]} \quad (10.29)$$

The above equations take into account a compensation for non-uniformities inherent in the screen for the four measurement locations for red, green, blue and white screen. R_W is the contrast in the image retention for the white area. R_R, R_G, R_B are defined similarly to R_W . See comments of 10.4 for a more detailed explanation.

REPORTING

Report the stress time T in hours (the agreed upon time interval, in the examples we show 6000 hours as an illustration only), the recovery time t_R and method (if applicable), video sample used, stress pattern with code values, signal range and quantization, configuration case (A or B), and the measured image retention contrasts of white R_W , red R_R , green R_G and blue R_B to no more than three significant figures. A graph describing luminance drop by periodical measurement can be reported as shown in FIGURE 10.32

COMMENTS

1. **Video sample:** IEC 62087-2:2015 broadcast contents and logo based broadcast contents are examples for TV application in SDR. IEC 62087-2:2015 internet contents and IEC TR 63274:2020 can be considered for monitor application in SDR and TV application in HDR, respectively. Other videos can be used as required. In deciding contents to use as stress patterns, the parties may wish to consider special cases pertinent to their application, such as the existence of fixed broadcaster logos, *e.g.*, CNN, NHK, KBS, HBO, or other static imagery that is overlaid on the video contents. The video content used shall be reported.
2. **Configuration of stress pattern:** Image retention usually occurs in regions where there are fixed objects such as logos or subtitles where stress from pixels is accumulated. The signal levels between regions of fixed objects and adjacent regions have typically been found to be the maximum and the average code value of the accumulated video frames. Although, in some cases, the calculated maximum code value may not occur in the fixed object region, the maximum code value of the accumulated image is used in this method to consider the most stressed pixel of the accumulated image from video content for image retention. The minimum code value can also be used instead of the average value as a stress pattern, if desired. The minimum, average and the maximum code values extracted from the IEC 62087 video samples, logo based broadcast contents for SDR, and IEC TR 63274:2020 for HDR, are shown in TABLE 10.19 and TABLE 10.20, respectively. The calculation procedure for code values from videos is illustrated to the right of FIGURE 10.28. For HDR, the SMPTE ST 2084 (PQ) EOTF is used and, as a guidance, the metadata below would be sent to the DUT:

Mastering display peak white luminance	1,000 cd m ⁻²
Mastering display black luminance	0 cd m ⁻²
Mastering display colorimetry	Rec. ITU-R BT.2020
Mastering display white point	D65
3. **Measurement:** 2D LMD can be considered if it is required. This measurement can be extended to be used with points other than those listed. An accelerated test can be used to reduce measuring time of image retention. If an accelerated test is used to estimate image retention, then the estimation method with detailed measurement conditions shall be reported. For the accelerated test, see IEC 62341-5-3 Annex A.
4. **Recovery:** If periodic recovery is required by the parties, measurements shall be taken with the same periodicity, and the results shall be reported before the final measurement.



TABLE 10.19. Code values of test pattern based on example video samples: IEC62087-2:2015 (@SDR)

Quantity	Value			
Video sample	IEC 62087-2:2015 broadcast contents 10 min. video loop		IEC 62087-2:2015 internet contents 10 min. video loop	
	8 bit		8 bit	
Signal quantization	8 bit		8 bit	
Range	Limited	Full	Limited	Full
V_{Rmin}	(31, 16, 16)	(17, 0, 0)	(24, 16, 16)	(9, 0, 0)
V_{Gmin}	(16, 31, 16)	(0, 17, 0)	(16, 43, 16)	(0, 32, 0)
V_{Bmin}	(16, 16, 27)	(0, 0, 13)	(16, 16, 65)	(0, 0, 57)
V_{Wmin}	(30, 30, 30)	(16, 16, 16)	(44, 44, 44)	(33, 33, 33)
V_{Rave}	(92, 16, 16)	(88, 0, 0)	(188, 16, 16)	(200, 0, 0)
V_{Gave}	(16, 89, 16)	(0, 85, 0)	(16, 192, 16)	(0, 205, 0)
V_{Bave}	(16, 16, 84)	(0, 0, 79)	(16, 16, 198)	(0, 0, 212)
V_{Wave}	(88, 88, 88)	(84, 84, 84)	(193, 193, 193)	(206, 206, 206)
V_{Rmax}	(111, 16, 16)	(111, 0, 0)	(234, 16, 16)	(254, 0, 0)
V_{Gmax}	(16, 107, 16)	(0, 106, 0)	(16, 234, 16)	(0, 254, 0)
V_{Bmax}	(16, 16, 104)	(0, 0, 103)	(16, 16, 234)	(0, 0, 254)
V_{Wmax}	(108, 108, 108)	(107, 107, 107)	(234, 234, 234)	(254, 254, 254)

TABLE 10.20. Code values of test pattern based on example video samples: logo based broadcast contents (@SDR)

Quantity	Value			
Video sample	Example #1 (96% of logo playback time) 12 min. video loop		Example #2 (97% of logo playback time) 12 min. video loop	
	8 bits		8 bit2	
Signal quantization	8 bits		8 bit2	
Range	Limited	Full	Limited	Full
V_{Rmin}	(31, 16, 16)	(18, 0, 0)	(63, 16, 16)	(55, 0, 0)
V_{Gmin}	(16, 31, 16)	(0, 17, 0)	(16, 57, 16)	(0, 48, 0)
V_{Bmin}	(16, 16, 31)	(0, 0, 17)	(16, 16, 55)	(0, 0, 45)
V_{Wmin}	(31, 31, 31)	(17, 17, 17)	(58, 58, 58)	(49, 49, 49)
V_{Rave}	(108, 16, 16)	(107, 0, 0)	(119, 16, 16)	(120, 0, 0)
V_{Gave}	(16, 104, 16)	(0, 102, 0)	(16, 111, 16)	(0, 111, 0)
V_{Bave}	(16, 16, 98)	(0, 0, 96)	(16, 16, 107)	(0, 0, 106)
V_{Wave}	(104, 104, 104)	(102, 102, 102)	(112, 112, 112)	(112, 112, 112)
V_{Rmax}	(175, 16, 16)	(185, 0, 0)	(150, 16, 16)	(156, 0, 0)
V_{Gmax}	(16, 174, 16)	(0, 184, 0)	(16, 144, 16)	(0, 149, 0)
V_{Bmax}	(16, 16, 169)	(0, 0, 178)	(16, 16, 141)	(0, 0, 145)
V_{Wmax}	(172, 172, 172)	(182, 182, 182)	(145, 145, 145)	(150, 150, 150)



TABLE 10.21. Code values of test pattern based on example video sample: IEC TR 63274:2020 (@HDR)

Quantity	Value	
Video sample	IEC TR 63274:2020 CLASP 10 min. video loop	
Signal quantization	10 bits	
Range	Limited	Full
$V_{R,min}$	(302, 0, 0)	(278, 0, 0)
$V_{G,min}$	(0, 281, 0)	(0, 253, 0)
$V_{B,min}$	(0, 0, 251)	(0, 0, 218)
$V_{W,min}$	(278, 278, 278)	(250, 250, 250)
$V_{R,ave}$	(373, 0, 0)	(361, 0, 0)
$V_{G,ave}$	(0, 365, 0)	(0, 351, 0)
$V_{B,ave}$	(0, 0, 347)	(0, 0, 330)
$V_{W,ave}$	(362, 362, 362)	(347, 347, 347)
$V_{R,max}$	(463, 0, 0)	(466, 0, 0)
$V_{G,max}$	(0, 454, 0)	(0, 455, 0)
$V_{B,max}$	(0, 0, 434)	(0, 0, 432)
$V_{W,max}$	(450, 450, 450)	(451, 451, 451)

TABLE 10.22. Measured data for the stress pattern extracted from IEC 62087-2:2015 considering a specific recovery procedure. Camera conditions: Exposure time 1/15s; F-stop $f/10$; Sensitivity ISO 200

Sample data only: Do not use any values shown to represent expected results of your measurements.

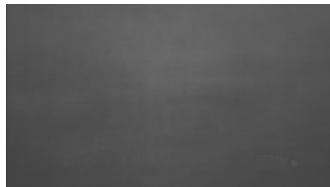


	White		Red		Green		Blue	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Initial measurement	L_{WC}	152.156	L_{RC}	31.009	L_{GC}	104.699	L_{BC}	13.202
	L_{WR}	166.988	L_{RR}	33.947	L_{GR}	114.819	L_{BR}	14.485
	L_{WL}	136.833	L_{RL}	28.527	L_{GL}	93.584	L_{BL}	12.223
	L_{WU}	156.381	L_{RU}	31.841	L_{GU}	106.701	L_{BU}	13.639
	L_{WD}	145.925	L_{RD}	29.580	L_{GD}	101.288	L_{BD}	12.567
Final measurement	K_{WC}	155.433	K_{RC}	30.620	K_{GC}	104.745	K_{BC}	12.738
	K_{WR}	176.791	K_{RR}	34.176	K_{GR}	121.749	K_{BR}	14.258
	K_{WL}	141.836	K_{RL}	29.892	K_{GL}	92.049	K_{BL}	12.881
	K_{WU}	159.857	K_{RU}	31.674	K_{GU}	109.005	K_{BU}	14.088
	K_{WD}	142.924	K_{RD}	29.329	K_{GD}	98.473	K_{BD}	11.241
Image retention factors	R_W	1.004	R_R	1.022	R_G	1.011	R_B	1.028

Measured conditions

Video sample	IEC62087:2015(Broad cast)	Range	Full
Signal quantization	8 bits	Configuration of stress pattern	Case A (average-maximum)
V_{Rave}	(88, 0, 0)	V_{Rmax}	(111, 0, 0)
V_{Gave}	(0, 85, 0)	V_{Gmax}	(0, 106, 0)
V_{Bave}	(0, 0, 79)	V_{Bmax}	(0, 0, 103)
V_{Wave}	(84, 84, 84)	V_{Wmax}	(107, 107, 107)
Stress time t	6000 h		
Acceleration assumption	Acceleration factor: $\frac{t_2}{t_1} = \left(\frac{J_2}{J_1}\right)^{m^{-1}} = 1$ <i>J</i> : Current density of OLED device in subpixel (proportional to luminance)		



Chapter 10 - Temporal Measurements

	m^{-1} : Coefficient depending on device. It is determined by measured luminance data.		
Recovery Procedures	<div>1. Power off for 1 hour and power on for 23 hours.</div> <div>2. Repeat power on, apply stress pattern and power off until final measurement.</div> <div>Note 1: Pixel refresher function may be applied by guidance of manufacturer, <i>e.g.</i>, activate the pixel refresher function for 1 hour if there is a pop-up message when display turned on.</div> <div>Note 2: Warm up procedure as shown in FIGURE 10.29 is applied if the next procedure is the final measurement.</div>		
Recovery time t_R	<div>250 hours (Power off for 1 hour per a day. (250 days))</div> <div>Note: Pixel refresher function and warm up time are not included in recovery time t_R (250hours).</div> <div>Pixel refresher running time and warm-up time may be added to recovery time., <i>e.g.</i>, $t_R = 253$ h (power off for 1 h \times 250 days + 2 times of pixel refresh + 1 h of warm-up time.</div>		
Accumulated image		Stress pattern	Photo of test results
			

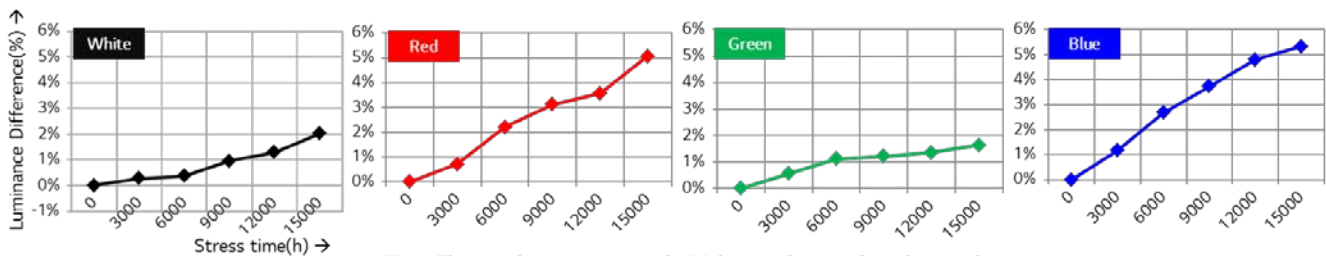
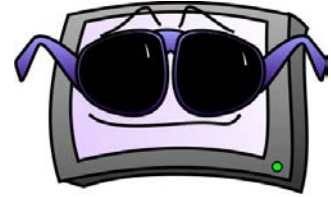


FIGURE 10.32. An example of stress time dependence of luminance drop for R, G, B, and W stress patterns.



11. REFLECTION & TRANSMISSION MEASUREMENTS

Extensive introductory material is supplied with this chapter because of the complications and difficulties encountered when making reflection and transmission measurements. Reflection properties are discussed further in the appendix as well: B17 Reflection Models & Terminology. We discuss how reflection and transmission-parameter measurement results can be combined and scaled to illuminance levels other than those used in the measurements. We briefly discuss how certain types of measurements can fail to produce reproducible results. We further discuss different ways that the source of light can be characterized and measured.



11.1 INTRODUCTORY REMARKS

Because of the complications associated with reflection and transmission measurements, we need to provide detailed introductory remarks that apply to this entire chapter. Table 1 provides a brief presentation of the reflection parameters to which we refer in this chapter (more information may be found in B17 Reflection Models & Terminology). It should be noted that ambient light and reflection enable reflective displays, but they interfere with emissive and transmissive displays, in general. Table 2 gives the corresponding transmission parameters.

Table 1. Reflection parameters to quantify reflection properties.

The parameters R , β , and ρ can have source/detector subscripts to help keep track of the apparatus geometry via the notation. Thus, $\beta_{d/8}$ refers to the luminance factor with a uniform diffuse source and the detector at 8° from the normal of the target material; $\rho_{8/d}$ refers to the reflectance with source at 8° from the target normal and the reflected light is measured with a diffuse detector (as with a sphere surrounding the target). Further specification for the diffuse measurement can be “di” that means diffuse with specular included and “de” that means diffuse with specular excluded.			
Parameter	Definition	Common Forms	Comment
reflectance factor ¹	$R = \left(\frac{\Phi_{\text{material}}}{\Phi_{\text{perfect diffuser}}} \right)_{\text{cone \& apparatus configuration}}$	$R = \frac{\pi L}{E},$ $R(\lambda) = \frac{\pi L(\lambda)}{E(\lambda)}$	Reflected flux of sample relative to flux from perfect reflecting diffuser. Here we must specify not only the apparatus geometry but also the detector measurement field and cone of the acceptance area.
Note: The reflectance factor is the preferred parameter to measure because it requires us to completely specify all of the measurement apparatus configuration including the source, the geometry, and the detector. In general, most optical measurements will depend upon the detector-display-illumination geometrical configuration. In such a case the reflectance factor should be used so that all important parameters are recorded. However, for the sake of simplicity, the luminance factor is used throughout this chapter.			
luminance factor or radiance factor ²	$\beta = \frac{L_{\text{material}}}{L_{\text{perfect diffuser}}} \Big _{\text{apparatus configuration}}$	$\beta = \frac{\pi L}{E},$ $\beta(\lambda) = \frac{\pi L(\lambda)}{E(\lambda)}$	Reflected luminance of sample relative to luminance from perfect reflecting diffuser. Must specify apparatus geometry but cone of luminance meter is assumed to not be important.
diffuse reflectance, or reflectance	$\rho = \frac{\Phi_{\text{diffuse}}}{\Phi_i} \Big _{\text{apparatus configuration}}$	$\rho_{0/d} = \beta_{d/0},$ $\rho(\lambda)_{0/d} = \beta(\lambda)_{d/0}$	Diffuse component of reflected flux to the total incident flux. Here we use uniform diffuse hemispherical detection, but is equivalent to β with uniform diffuse illumination: $\rho_{0/d} = \beta_{d/0}$.



regular (or specular) reflectance ³	$\zeta = \frac{\Phi_{\text{specular}}}{\Phi_i} \bigg _{\text{apparatus configuration}}$	$\zeta = \frac{L}{L_s}$ $\zeta(\lambda) = \frac{L(\lambda)}{L_s(\lambda)}$	Flux reflected into the regular (specular) direction relative to the total incident flux. This is the ratio of the net reflected luminance L to the source luminance L_s in the regular direction.
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¹To avoid confusion with the radiometric reflectance factor, we will often use luminous reflectance factor for the photometric term. ²The equivalent to luminance factor in radiometry is radiance factor $\beta(\lambda)$. ³The CIE uses ρ_r for regular/specular reflectance that refers to only the mirror like reflection not diffused. In this chapter, 'regular reflectance' will describe reflection measurements that uses the regular (specular) configuration and measures a reflected luminance in the regular (specular) direction that may include specular and/or diffused light.

Table 2. Transmission parameters to quantify transmission properties.

The parameters T and τ have similar source/detector subscripts as the reflection parameters to help keep track of the apparatus geometry. Thus, $\tau_{d/0}$ refers to the transmittance with a uniform diffuse source and the detector at 0° from the normal of the target material. An additional specification for the diffuse measurement can be "di" that means diffuse with regular included and "de" that means diffuse with regular excluded.

Parameter	Definition	Common Forms	Comment
transmittance factor ¹	$T = \left(\frac{\Phi_{\text{material}}}{\Phi_{\text{perfect diffuser}}} \right) \bigg _{\text{cone \& apparatus configuration}}$	$T = \frac{\pi L}{E},$ $T(\lambda) = \frac{\pi L(\lambda)}{E(\lambda)}$	Transmitted flux of sample relative to flux transmitted by perfect transmitting diffuser. We must specify not only the apparatus geometry but also the detector measurement field and cone of the acceptance area.
Note: The transmittance factor is the most complete parameter to measure because it requires us to completely specify all the measurement apparatus including the source, the geometry, and the detector.			
transmittance	$\tau = \frac{\Phi_{\text{total}}}{\Phi_{\text{input}}}$	$\tau = \frac{\Phi_{di}}{\Phi_s}$ $\tau(\lambda) = \frac{\Phi_{di}(\lambda)}{\Phi_s(\lambda)}$	Ratio of the total transmitted flux to the incident flux, measured using uniform diffuse hemispherical detection. It assumes that all the transmitted light is measured.
diffuse transmittance	$\tau = \frac{\Phi_{\text{diffuse}}}{\Phi_{\text{input}}} \bigg _{\text{apparatus configuration}}$	$\tau = \frac{\Phi_{de}}{\Phi_s}$ $\tau(\lambda) = \frac{\Phi_{de}(\lambda)}{\Phi_s(\lambda)}$	Ratio of the transmitted diffuse flux to the incident flux, measured using uniform diffuse hemispherical detection but excluding the flux from the regular direction.
regular transmittance ²	$\tau_r = \frac{\Phi_{\text{regular}}}{\Phi_i} \bigg _{\text{apparatus configuration}}$	$\tau_r = \frac{L}{L_s}$ $\tau_r(\lambda) = \frac{L(\lambda)}{L_s(\lambda)}$	Ratio of the net transmitted luminance L to the source luminance L_s in the same detection solid angle and direction (usually normal to the display surface).

¹To avoid confusion with the spectral transmittance factor, we will often use luminous transmittance factor for the photometric term. ²The CIE uses τ_r for regular transmittance, which refers to light that is largely undeviated (not diffusely scattered) from its optical axis as it passed through the sample. A measurement using the regular transmittance configuration may include diffused light.

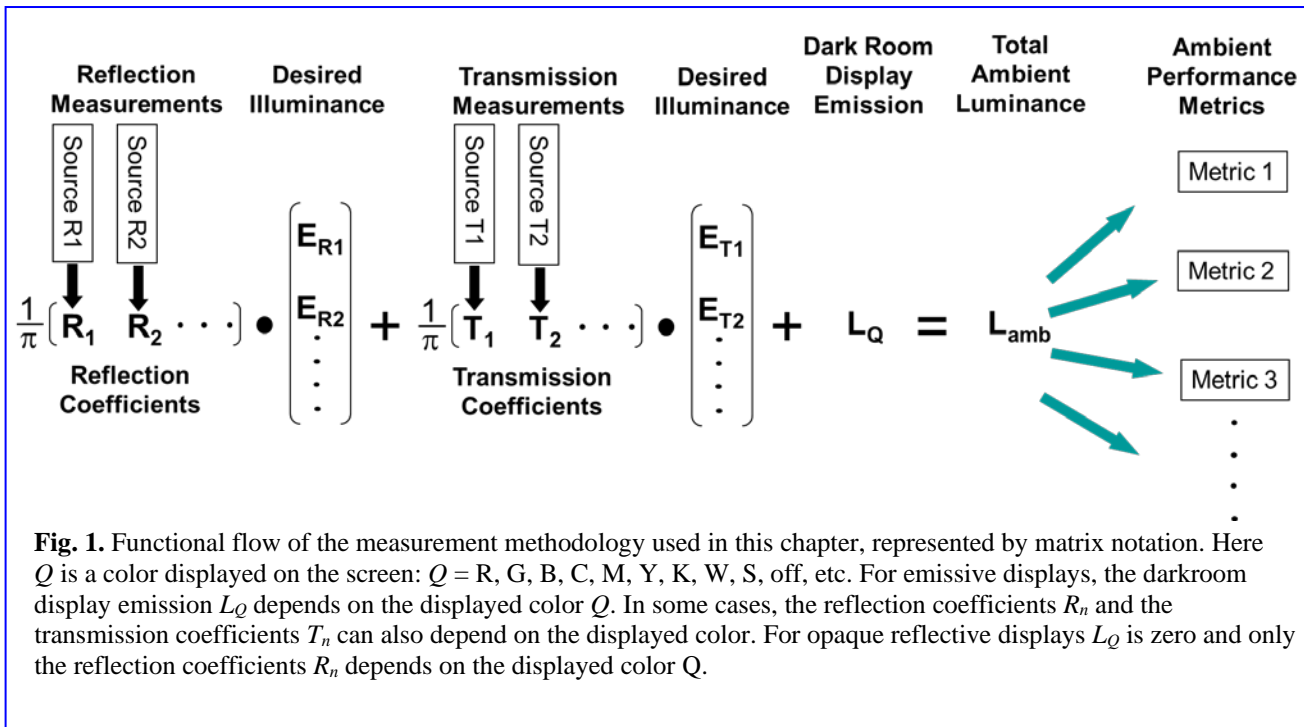


11.1.1 LINEAR SUPERPOSITION & SCALING

In most cases, displays are viewed in an ambient illumination environment. The displays considered here can carry information by modulating the emitted light (emissive displays), the reflected light (reflective displays) or the transmitted light (transmissive displays)¹. In most cases, the light reflected by reflective displays or transmitted by transmissive displays comes from the ambient illumination environment. Quantifying the amount of ambient light that is reflected from or transmitted through the display to the eye depends on the source-detector geometry, the reflection properties, and the transmission properties of the display. Therefore, a display's reflection and transmission properties need to be characterized in order to determine what the performance of a display will be under any given ambient illumination condition. Once determined, these properties can be combined with a display's intrinsic information-carrying properties of emission, reflection, and/or transmission to calculate important metrics such as ambient contrast and ambient color gamut.

In most cases, the reflection and transmission of light for displays can be treated as a linear response system. (Displays that exhibit significant photoluminescence are beyond the scope of this chapter.) This characteristic then enables us to harness the power of scaling and linear superposition. Since the amount of light reflected or transmitted by a display in a given geometry is proportional to the incident illumination, the reflection and transmission metrics of the display can be measured once at a given illumination level, then used to predict the amount of reflected and transmitted light for any other illumination level. In addition, by separately measuring the display's reflection and transmission properties for each type of light source (e.g. directed, hemispherical-diffuse), we can predict (by linear superposition) what the total contribution would be if all these sources were present. For example, the display's reflection properties in ambient daylight can be characterized for the hemispherical illumination of skylight, and the directed illumination of sunlight. Both of these are combined to determine the net effect of daylight illumination.^{2, 3} An example of a transparent display receiving ambient daylight from the back and indoor lighting from the front is shown in Fig. 2.

This chapter utilizes the scaling and linear superposition properties of the measured reflection and transmission coefficients to calculate the performance characteristics of the display under ambient illumination. In certain rare situations, if the display system is not linear under the proposed ambient conditions, this method cannot be used. For instance, an avionics



¹ Manufacturers keep developing new ways to deliver visual information, combining emissive, reflective and transmissive display technologies. Examples include hybrids of reflective displays with emissive display or front light sheets, transmissive LCD without an emissive component but with switchable opacity or reflectivity (shuttering opacity mask), and transmissive displays with an emissive component, for example LCD with transparent backlight or transparent OLED displays where scattering of the emitted light within the display can make it opaque (opacity through light).

² E. F. Kelley, M. Lindfors, and J. Penczek, Display daylight ambient contrast measurement methods and daylight readability, J. Soc. Information Display, V 14, p. 1019-1030 (2006)

³ J. Penczek, E. F. Kelley, and P. A. Boynton, General framework for measuring the optical characteristics of displays under ambient illumination, J. Soc. Information Display, V 23, p. 529-542 (2015)



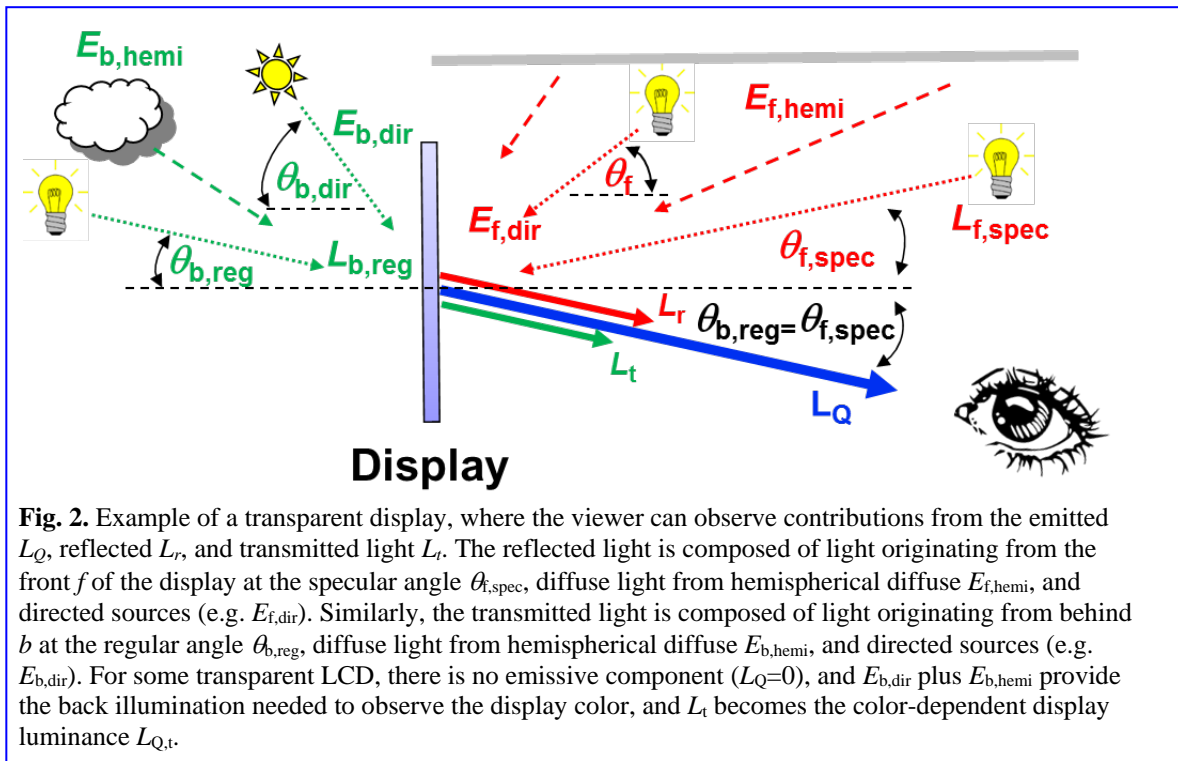
cockpit display may be subjected to high light levels due to solar loading during use. Such an ambient condition may cause optical changes in the display system due to heating and light-induced leakage in an active-matrix LCD. These effects will not be evident at lower illumination levels. The functional framework of this methodology is outlined in Fig. 1.

The ambient environment of the intended display application needs to first be defined. This would include the orientation of the display relative to the detector viewing direction, the type and position of light sources, and the color and pattern of the display content. Each of the individual source geometries is then simulated in a controlled laboratory environment by selecting the most appropriate measurement option from those listed in this section. The result from each of these measurements will be a reflection or transmission coefficient that represents the response of the display to that illumination-detection geometry. The relative contribution of this source geometry to the detected signal is determined by scaling the reflected or transmitted light to the desired illumination level for that source. The total ambient luminance (or spectral radiance) is the sum of all the source reflections, source transmissions, and any emission from the display itself. Once this total luminance is calculated for the desired lighting environment, it can be used to calculate a variety of ambient performance metrics. It may be necessary to repeat the measurements and total luminance calculation for other display colors Q in order to complete the metric calculation.

In the general case (e.g. transparent displays), the total ambient luminance L_{amb} measured by a detector viewing the display from a defined direction is illustrated in Fig. 2 and can be expressed in the following form:

$$L_{amb} = L_Q + L_r + L_t = L_Q + L_{refl,dif} + L_{refl,reg} + L_{trans,dif} + L_{trans,reg} \quad (1)$$

where L_Q is the darkroom luminance of a given display color Q with $Q = R, G, B, C, M, Y, K, W, S, \text{off}$, etc. (S is for gray shade, and the reflection or transmission properties for the display off can be different than for black, K), $L_{refl,dif}$ is the luminance that arises from diffuse reflections, $L_{refl,reg}$ is the luminance from regular (or specular) reflections in the specular direction, $L_{trans,dif}$ is the luminance that arises from diffuse transmissions, and $L_{trans,reg}$ is the luminance from regular transmissions in the viewing direction. For reflections, the term “regular” (or “specular”) refers to the mirror-like reflections that follow the laws of geometric optics, like reflections from a mirror. Displays that have a dominant specular reflection component produce a distinct virtual image of a reflected object viewed in the specular direction. Regular transmitted light is observed mainly from a source which is in the viewing direction. Diffuse reflection and transmission arises from light that is scattered out of (or away from) the regular direction of reflection (or transmission). For example, anti-glare surfaces can almost completely scatter the specular reflection component into a diffuse one, referred to as regular scatter or haze as shown in Fig. 3 and 4. In general, a display can exhibit both specular and diffuse reflection/transmission properties, as illustrated by Fig. 2. Note that in reflective displays L_Q is zero. Also note that, depending on the display technology, the contributions from the emitted, reflected and/or transmitted light can depend on the display color and thus have to be measured separately for



each of the given display colors Q .



As suggested by the reflection example in Figure 3, for a display that significantly scatters the reflected light, a luminance measurement in the regular direction would usually include both diffuse and specular reflection components. A similar situation can occur in transmission. When both diffuse and regular reflection or transmission components are present at a given detector viewing direction, we call this mixed reflection or transmission. In reflection, the relative contribution of the diffuse and specular reflection components can often be better understood by examining the in-plane bidirectional reflectance distribution function (BRDF) profile of the display for a given light source. In principle, the BRDF profile can be determined by measuring the luminance distribution along the dashed red line drawn in Fig. 3. Alternatively, the detector can be positioned at a fixed angle and the light source can be moved in-plane over a range of inclination angles. Figure 4 illustrates this measurement geometry and gives an example of an in-plane BRDF profile. A similar profile can also be obtained in transmission by measuring the in-plane bidirectional transmittance distribution function (BTDF).

Fig. 4b) illustrates that the diffuse reflection can be composed of a Lambertian component, which is constant over source inclination angles, and a diffuse haze component that is centered about the specular direction. The components, specular, haze, and Lambertian are not entirely independent. The incident light energy is shared among them. Displays that have an anti-glare surface can have a strong haze component that completely diffuses the specular reflection component. It is evident from this graph that the size of the detector's measurement field angle will affect the relative amount of detected reflection and alter the magnitude of the reflection coefficient determined for this illumination-detection geometry. Without a high-resolution BRDF measurement of the reflection properties it is difficult to separate the specular reflection component from the diffuse reflection components.

It is useful to think of an extended light source as a cluster of multiple adjacent point sources. If the surface scatters the light into all three (specular, haze, and Lambertian) components, each individual point source may have a luminance distribution similar to Fig. 4b). As the light source gets larger, the scatter distributions from each point source overlap and add to the total luminance in a given viewing direction. This concept is illustrated in Fig. 5a), where the luminance profile for a 1° subtense light source can be constructed from a grid of individual point source luminance profiles. As the light source gets larger (Fig. 5b)), more and more point sources are added. The specular component of each point source is the same at each location in space (and angle), but their diffuse (haze plus

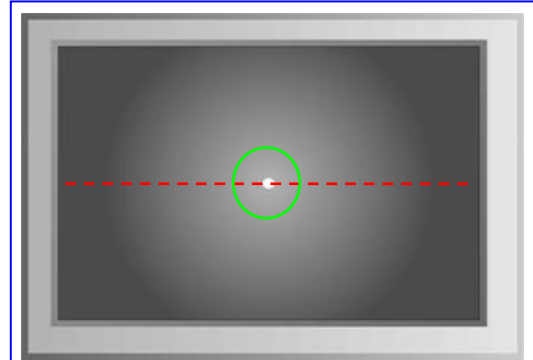


Fig. 3. Illustration of a display that has diffuse (Lambertian and haze) and specular reflection properties. The center bright white spot is the distinct virtual image of a small source viewed in the regular (specular) direction. The fuzzy gray ball around the bright spot is the diffuse haze component, and the background gray is the diffuse Lambertian component. A typical luminance measurement in the specular direction would subtend a measurement field area (defined by the detector) that is centered about the bright white spot and is represented by the green circle.

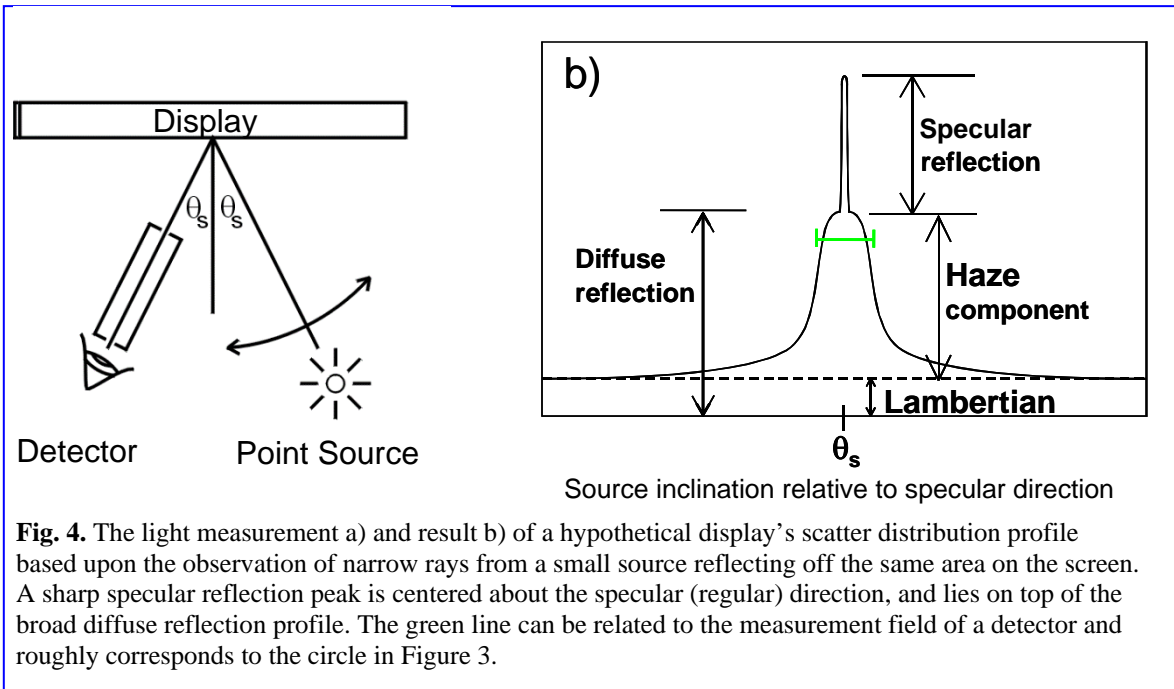


Fig. 4. The light measurement a) and result b) of a hypothetical display's scatter distribution profile based upon the observation of narrow rays from a small source reflecting off the same area on the screen. A sharp specular reflection peak is centered about the specular (regular) direction, and lies on top of the broad diffuse reflection profile. The green line can be related to the measurement field of a detector and roughly corresponds to the circle in Figure 3.

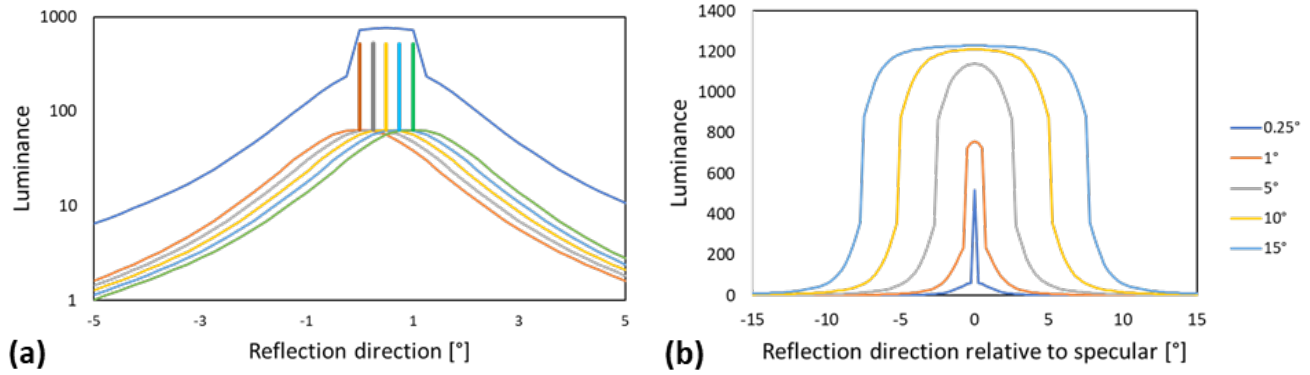


Fig. 5. Illustration of how an extended source can be visualized as an assembly of point sources with overlapping luminance scatter profiles. The left plot shows how a 1° subtense light source (dark blue) is composed of the individual point sources. While the specular contribution at each point is the same, the cross-scatter from the neighbors cause the diffuse component to grow. The right plot extends this concept up to a 15° subtense light source, showing how the haze component can grow through contributions from the neighboring point sources. However, the haze contribution will saturate at the larger source sizes once the source has become wider than the haze luminance distribution. This would not be true for Lambertian scatter, which would theoretically remain constant at all angles.

Lambertian) contributions overlap and increases with the size of the source as more scattered light comes from the growing number of overlapping adjacent sources.

As emitted, reflected and transmitted light is additive, we re-formulate the total luminance in Eq. (1) as a summation of all sources in the front and back hemisphere of the display that contribute light in the detector's defined viewing (specular) direction:

$$L_{\text{amb}} \approx L_Q + L_{f,\text{dif}} + L_{f1,\text{dir}} + L_{f2,\text{dir}} + \dots + L_{b,\text{dif}} + L_{b1,\text{dir}} + L_{b2,\text{dir}} + \dots, \quad (2)$$

where $L_{f,\text{dif}}$ and $L_{b,\text{dif}}$ are the luminance values produced by uniform diffuse hemispherical illumination on the front and back of the display, $L_{f1,\text{dir}}$ and $L_{f2,\text{dir}}$ are the luminance contributions reflected from discrete directed sources in front of the display, $L_{b1,\text{dir}}$ and $L_{b2,\text{dir}}$ are the luminance contributions transmitted from discrete directed sources from behind the display. This is an approximation assumes that the contribution from the hemispherical area obscured by the directed source is negligible. The luminance from the front (and back) hemispherical illumination can be measured with the specular (regular) direction included ($L_{f,\text{hemi:si}}$ ($L_{b,\text{hemi:si}}$) or excluded ($L_{f,\text{hemi:se}}$ ($L_{b,\text{hemi:se}}$):

$$L_{\text{amb}} \approx L_Q + L_{f,\text{hemi:si}} + L_{f1,\text{dir}} + L_{f2,\text{dir}} + \dots + L_{b,\text{hemi:si}} + L_{b1,\text{dir}} + L_{b2,\text{dir}} \quad (\text{hemispherical with specular included}), \quad (3)$$

or

$$L_{\text{amb}} \approx L_Q + L_{f,\text{hemi:se}} + L_{f,\text{dir:se}} + L_{f1,\text{dir}} + L_{f2,\text{dir}} + \dots + L_{b,\text{hemi:se}} + L_{b,\text{dir:se}} + L_{b1,\text{dir}} + L_{b2,\text{dir}} \quad (\text{hemispherical with specular excluded}). \quad (4)$$

A mixture of specular/regular excluded and included is also possible between the front and back hemispherical illumination. This formalism has one source that produces a contribution from the hemispherical illumination, allows discrete directed sources in front of and/or behind the display to illuminate the display from directions other than the regular direction, and allows one of the sources to represent the specular/regular direction. Equation (3) combines both contributions into one term, since this case can be expressed by one reflection and transmission coefficient. The use of Equation (3), Equation (4), or a mixture of the two, depends on the intended application of the display. For example, Equation (3) would be the most appropriate if a transparent display is used outdoors with the sky viewed in the specular direction ($L_{f,\text{hemi:si}}$), the sun is off-specular ($L_{f1,\text{dir}}$), and the sky is also viewed through the display ($L_{b,\text{hemi:si}}$) without a direct sun contribution ($L_{b1,\text{dir}}=0$). However, if the transparent display is tilted so that the viewer sees him/herself in reflection while the transmitted view remains the same, then the necessary equation would be a mixture of Equation (3) and (4). In this latter case, while the transmitted contribution would be the same, the reflected specular-excluded 'hole' in the hemispherical measurement $L_{f,\text{hemi:se}}$ must be filled by the specular source $L_{f,\text{dir:se}}$ (the luminance of the viewer's body reflected in the display) in order to complete the illumination scenario. In either case, the illumination terms in the above equations can be represented by their reflection and transmission coefficients. Note that for transmissive displays whose transmission coefficients $T_{Q,n}(\lambda)$ depend on the displayed color Q , all transmissive luminance terms $L_{Q,b,\text{hemi}}$ and $L_{Q,n,\text{dir}}$ in Equations (3) and (4) become color



dependent. Also note that for an opaque reflective displays L_Q is zero, and all the above reflection terms must be measured for each display color Q .

For display reflections, we will mainly characterize the reflection properties of the display by two reflection metrics, the radiometric or photometric reflectance and the radiance or luminance factor (even though the reflectance factor would be preferred). Reflectance is the ratio of the reflected radiant or luminous flux to the incident flux. Whereas the luminance factor is π times the ratio of the luminance to the illuminance (or radiance to the irradiance; the reflectance factor is a ratio of the display's reflected flux to that of a perfect reflecting diffuser measured under identical conditions). Both the reflectance and the radiance or luminance factor can be strongly dependent on the measurement configuration geometry.

For light transmitted through the display, an analogous approach is used for measuring the display's transmission properties. Since the transmission measurements are often strongly dependent on the measurement configuration, the transmittance factor will be mainly used. Both the radiometric and photometric forms of the transmittance factor will be employed. The spectral transmittance factor is usually necessary in order to properly evaluate color results, especially in cases where the transmission coefficients $T_{Q,n}(\lambda)$ depend on the displayed color Q . The results of these measurements must be reported with a detailed description of the illumination and detection geometrical conditions. For a more detailed discussion on reflection and transmission concepts, see the appendix (B17 Reflection and Transmission Models & Terminology).

11.1.2 PHOTOMETRIC AND SPECTRAL MEASUREMENTS

The reflection parameters of a display can be measured spectrally or photopically as weighted by the spectral luminous efficiency of the human eye, $V(\lambda)$. The measurement procedures in this section are usually designed to allow for both spectral or photometric measurements to be made. If a spectroradiometer and a spectrally calibrated white diffuse reflectance standard are available, then it is highly desirable to measure the spectral reflectance, spectral radiance factor, or spectral reflectance factor of the display. By knowing these spectral functions, the user is able to use linear superposition to calculate the ambient performance of the display (e.g. ambient contrast ratio and ambient display color) for any light source spectra or illumination level at the same illumination-detection geometry. This enables the spectral measurements to be conducted using a light source like CIE Illuminant A, but the ambient contrast can be calculated for CIE Illuminant D65. Therefore, spectral measurements greatly relax the spectral constraints on the light source, and significantly expands the capability for analyzing the display performance metrics. In contrast, if (luminous) reflectance, luminance factor, or luminous reflectance factor measurements are made using a luminance meter, then the subsequently derived ambient performance metrics might be only strictly valid for a source with the same spectral distribution.

How much uncertainty the photometric measurements will manifest depends upon the color of the display screen and the color of the illumination. When examining grays (gray, black, white, off) with broadband illumination, the deviations in the resulting luminance factors ($\beta = \pi L/E$) can be relatively small despite such remarkably different spectra from 16500 K skylight to 2856 K tungsten filament lighting. The maximum deviation in the luminance factor can be less than 6 % between the tungsten-halogen source and the blue skylight source. *This could suggest that the source spectrum for most broadband sources will not seriously affect the photopic measurement of the reflection parameters of gray-like displays if such uncertainties of approximately 6 % are acceptable.* When strong colors of the display are involved, the source of illumination is not broadband, or a high accuracy is required, then it may be best to make spectrally resolved measurements.

To illustrate the relationship between the photometric and spectrally resolved reflectance factor methods, an example analysis is presented for a display under ring-light illumination. Equation (5) defines the parameters required to obtain the luminous reflectance factor R_Q :

$$R_Q = R_{\text{std}} \frac{L_{Q,\text{Ring}} - L_Q}{L_{\text{std}}} \quad (5)$$

where L_Q is the luminance at the center of the display color pattern in a darkroom with the ring-light OFF, $L_{Q,\text{Ring}}$ is the luminance of the display with the ring-light ON, L_{std} is the luminance from a white reflectance standard put in place of the display with the ring-light illumination ON, and R_{std} is the known luminous reflectance factor of the white standard determined under the same spectral and geometric illumination conditions (it is *not* the value obtained under diffuse illumination). The spectral equivalent of that equation is given by the following spectral reflectance factor $R_Q(\lambda)$ relation:

$$R_Q(\lambda) = R_{\text{std}}(\lambda) \frac{L_{Q,\text{Ring}}(\lambda) - L_Q(\lambda)}{L_{\text{std}}(\lambda)} \quad (6)$$

where $L_Q(\lambda)$ is the spectral radiance at the center of the display color pattern in a darkroom (L_Q is zero for reflective displays), $L_{Q,\text{Ring}}(\lambda)$ is the spectral radiance of the display with the ring-light ON, $L_{\text{std}}(\lambda)$ is the spectral radiance from the



white reflectance standard put in place of the display with the ring-light ON, and $R_{\text{std}}(\lambda)$ is the known spectral reflectance factor of the white standard determined under the same spectral and geometric illumination conditions (it is *not* the value obtained under diffuse illumination). As Equations (5) and (6) show, the functional form of the equations is the same. However, the photometric parameters are replaced by spectrally resolved parameters. This will be the case for all the reflection measurements. Thus, for simplicity, only the photometric form will be given for each particular reflection measurement.

If spectral reflection measurements are made, the spectral reflectance or reflectance factor $R_Q(\lambda)$ can be used to calculate the luminous reflectance or reflectance factor R_Q for any illumination spectra $E(\lambda)$ by using the following expression:

$$R_Q = \frac{\int_{\lambda} R_Q(\lambda) E(\lambda) V(\lambda) d\lambda}{\int_{\lambda} E(\lambda) V(\lambda) d\lambda} \quad (7)$$

where $V(\lambda)$ is the spectral luminous efficiency function for photopic vision. For spectral distributions of daylight illuminants at a given CCT, follow the relation used by publication CIE 15 Colorimetry:

$$E(\lambda) = E_0(\lambda) + M_1 E_1(\lambda) + M_2 E_2(\lambda) \quad (8)$$

where the E_0 , E_1 , and E_2 eigenfunctions are tabulated in CIE 15, and the M_1 and M_2 eigenvalues for the case of Illuminants D50 and D65 are given in Table 3. The relative spectral distributions of other standard sources are tabulated in CIE 15 as well.

Table 3. Eigenvalues for several daylight illuminants per publication CIE 15.

Correlated Color Temperatures	Eigenvalues	
	M_1	M_2
5000 K	-1.0401	0.36666
6500 K	-0.29634	-0.68832
7500 K	0.14358	-0.75993

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



11.1.3 SOURCE MEASUREMENT AND CHARACTERIZATION

In all reflection measurements the source of illumination must be specified by its geometry and quantity of illumination. Depending upon the reflection parameter being measured, the illumination from a source can be specified by the illuminance at the measurement field or the luminance of the source. The uniformity of the source and/or its uniformity of illuminance may also need to be characterized in order to assure reproducible measurement results. Several types of sources may be employed for making reflection measurements: (1) integrating spheres, (2) discrete or directed uniform sources and ring-light sources, (3) collimated sources, and (4) converging sources.

11.1.3.1 Integrating-Sphere Sources for Uniform-Diffuse Surrounds:

When we use an integrating sphere or sampling sphere to produce a uniform diffuse illumination surround, we need to know the illuminance at the measurement field (area of measurement). The illuminance must be measured with the display in place. We cannot measure the luminance of the display and then remove the display and replace it with a reflection sample to measure the illuminance. The illuminance must be measured at the same time the display is measured without changing anything in the integrating sphere. For a small display in a large integrating sphere, a reflectance standard can be placed in the vicinity of the measurement field. There are several ways to measure the illuminance:

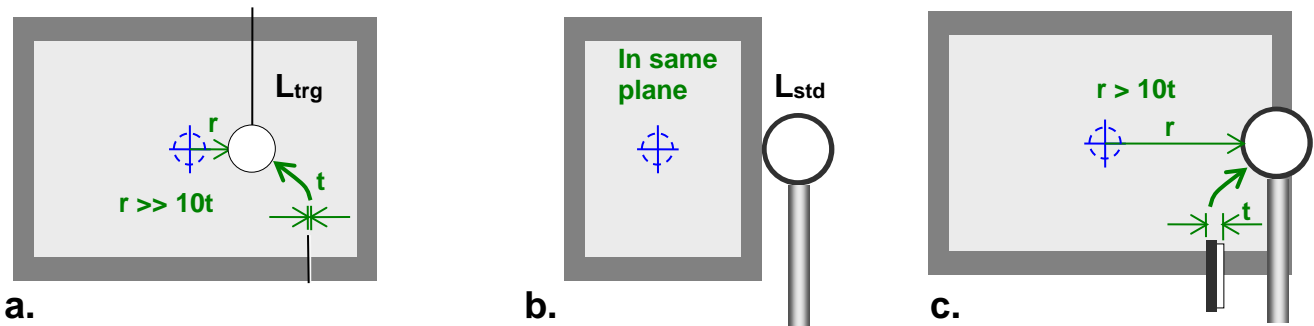


Fig. 6. Guidance for placement of a white standard or white (or gray) target near the display for making illuminance measurements under uniform diffuse illumination conditions inside an integrating sphere (the blue + and dashed circle marks the measurement field): (a) a thin calibrated matte white target with an opaque backing (preferred situation with larger displays) held in place with a thin stick, wire, or thread; (b) white reflectance standard placed next to a small display and placed in the same plane as the display surface; and (c) white reflectance standard placed in front of the display (least preferred situation).

1. Thin Target: Calibrated spectrally flat white or gray matte target made of thin material with a thin opaque (black or metal) backing, the luminance L_{trg} of which indicates the illuminance—see Fig. 6a. The illuminance is given by

$$E = \pi L_{trg} / \rho_{trg} , \quad (9)$$

where ρ_{trg} is the diffuse reflectance of the target material. The advantage of using a thin target is that it can be placed near the measurement field when using either an integrating sphere with the display at the center of the sphere or it can be used with a sampling sphere where it is included with the display sample at the sample port. Because it is thin it is less likely to obstruct light from entering the measurement field and it can be placed essentially in the same plane as the sample display surface. The calibration of the target is accomplished by placing it next to a known white reflectance standard of diffuse reflectance ρ_{std} at the center of an integrating sphere or in the plane of the sample port of a sampling sphere—see Fig. 7. The target reflectance is given by

$$\rho_{trg} = \rho_{std} L_{trg} / L_{std} . \quad (10)$$

Note that this diffuse reflectance ρ_{std} and the calibrated target reflectance ρ_{trg} are *only* used for uniform diffuse hemispherical illumination as found in an integrating sphere and sampling sphere. These reflectance values must *not* be used in conjunction with directed sources, collimated sources, or discrete sources.

2. White Standard: White reflectance standard in the vicinity of the measurement field—see Fig. 6b and 6c. This can be useful in an integrating sphere that contains the entire display at its center. Such a sphere must be significantly larger than the display in order to provide uniform illumination (the rule of thumb is that the sphere diameter must be from four to seven times the maximum size of the display). The illuminance is given by

$$E = \pi L_{std} / \rho_{std} , \quad (11)$$



where ρ_{std} is the diffuse reflectance of the white reflectance standard and L_{std} is its luminance. It is best to have the surface of the standard in the plane of the surface of the screen as can be arranged in Fig. 6b. Placing the standard in front of the display as in Fig. 6c is not as wise because they are now in different planes and the white standard can prevent some of the light from reaching the measurement field because of shadowing.

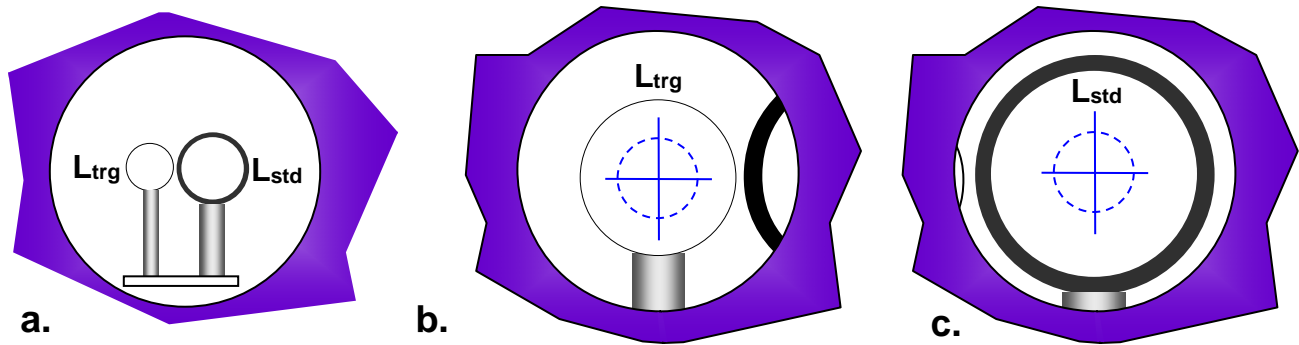


Fig. 7. Calibration of thin white target with opaque backing against a white reflectance standard within an integrating sphere. Looking through the measurement port (exit port): (a) View through the measurement port where the white target and standard are placed side-by-side at the center of the integrating sphere; (b) Measuring the luminance of the white target; (c) measuring the luminance of the white standard. The + with dashed circle represents the measurement field of the luminance meter.

3. Photodiode Monitor: A photopic photodiode that indicates the illuminance is often used in spheres. The problem with such a detector is that the photopic response is not necessarily the same as the luminance meter used to measure the luminance of the display. In case of strong colors, rather strong errors can occur with the photopic filtering. For such strong colors a spectral measurement is wisest using a white standard or white target instead.

4. Wall Luminance (Sampling Sphere): In Fig. 8 we use a properly designed sampling sphere, and we are looking through the measurement port to the opposite wall where the sample port is located—see § 11.3.2 Sampling-Sphere Implementation. A measurement of the luminance L_{wall} can be used to indicate the illuminance at the sample port. The diffuse reflectance of the wall is given by

$$\rho_{\text{wall}} = \rho_{\text{std}} L_{\text{wall}} / L_{\text{std}} \quad (12)$$

The illuminance at the exit port will then be provided by

$$E = \pi L_{\text{wall}} / \rho_{\text{wall}} \quad (13)$$

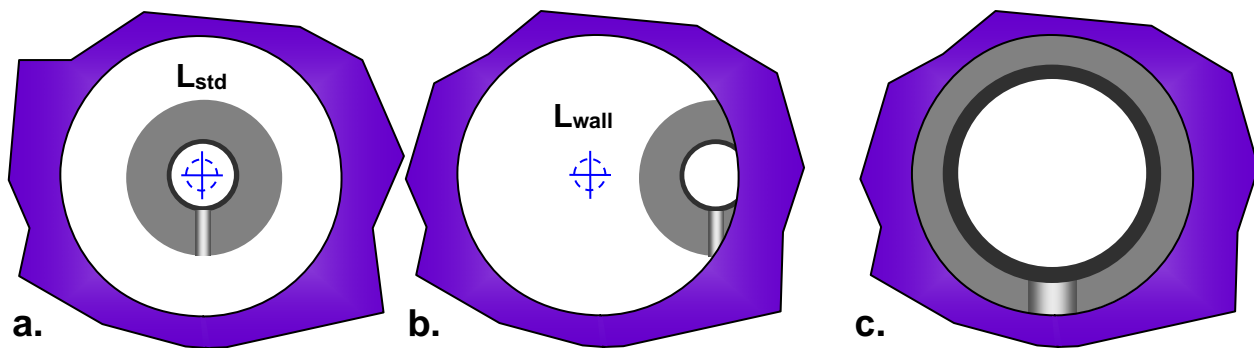


Fig. 8. Calibration of the wall reflectance based upon the white reflectance standard when we use a sampling sphere. The white standard is placed with its surface parallel with the plane of the sample port on the far wall. The luminance of the white standard is measured (a), and the luminance of the wall is measured (b) without changing the position of the white standard. The luminance meter is moved from side to side to always keep the measurement field centered. In this figure, the measurement port is shown to be very large in (a) and (b) for the purposes of illustration. In practice the detector would be moved back away from the measurement port so that it only sees the sample port and not the white surrounding the sample port as in (c) where the white standard is being measured.



11.1.3.2 Discrete or Directed Uniform Sources and Ring-lights:

In several reflection measurement methods, discrete uniform sources are employed such as shown in Fig. 9. (The use of a ring-light is shown in § 11.5 Ring-Light Reflection.) How uniform these sources must be is difficult to say. In making a specular measurement on a display that has only a specular component, the luminance of the center of the uniform source is what matters. However, when more complicated reflection properties are involved such as haze or matrix scatter, then the uniformity of the source can be more of a factor.

Typically, uniform source specifications state 1 % nonuniformity. We would state that at least a 1 % nonuniformity would be required in general and should be a simple matter to attain. Our method to determine nonuniformity is to measure the uniform source at its center and then eight other places (top, bottom, left, right, and the diagonals) from 75 % to 80 % of the radius from the center to the edge of the exit port as shown in Fig. 8. Determine the average μ and standard deviation σ of the set of nine luminances L_i and define the nonuniformity n as the ratio

$$n = \sigma / \mu. \quad (14)$$

The nonuniformity n should be less than 1 %, $n < 0.01$.

Illuminance Measurements and Target

Calibration: When such sources are used for illumination, it must be remembered that white reflectance standards and any

calibrated white or gray targets are *not* Lambertian; that is, in the expression for the luminance of such a material, $L = \beta E / \pi$, the luminance factor β is *not* a constant independent of the direction of illumination as it would be for a Lambertian material. Such standards are generally only calibrated for uniform diffuse illumination conditions. If they are used for any other type of illumination they *must* be calibrated for that illumination geometry. A good illuminance meter (or irradiance meter) placed in the plane of the display surface (with the display moved out of the way) and aligned with the normal of the display may be the best alternative. For some sources, ones that are close to the display, the light from the display can influence the source luminance and illuminance. A method to account for this is shown in Fig. 10.

Figure 10a shows the source-display-detector arrangement. In Fig. 10b we have removed the display and placed a cosine-corrected illuminance meter exactly at the position of the measurement in the plane of the display surface to obtain an illuminance E_{cal} . It is also very helpful to have a photopic photodiode monitor in the source to separately monitor the interior of the source; let it exhibit a photocurrent of J_{cal} . In Fig. 10c we have removed the illuminance meter and have replaced it with our small thin white target (white or gray matte material with an opaque backing), which is placed at the measurement point also in the plane of

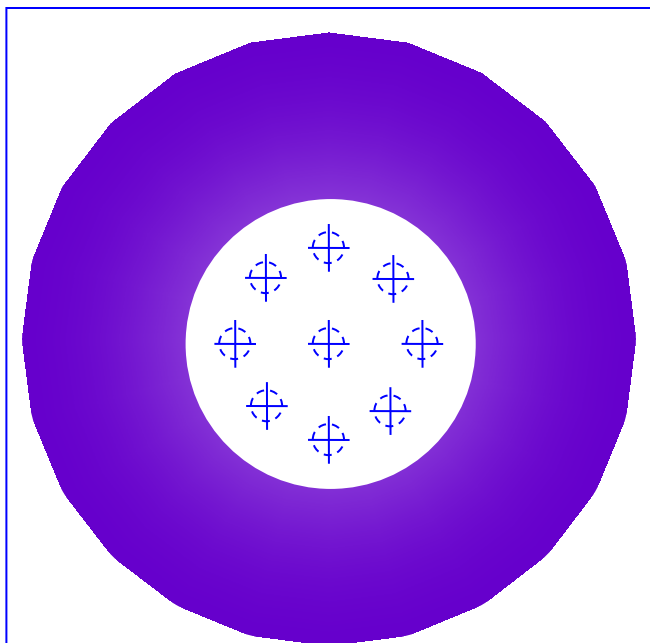


Fig. 9. Uniform source showing nine measurement points for determining nonuniformity. The blue + with dashed circle represents the measurement field of the luminance meter.

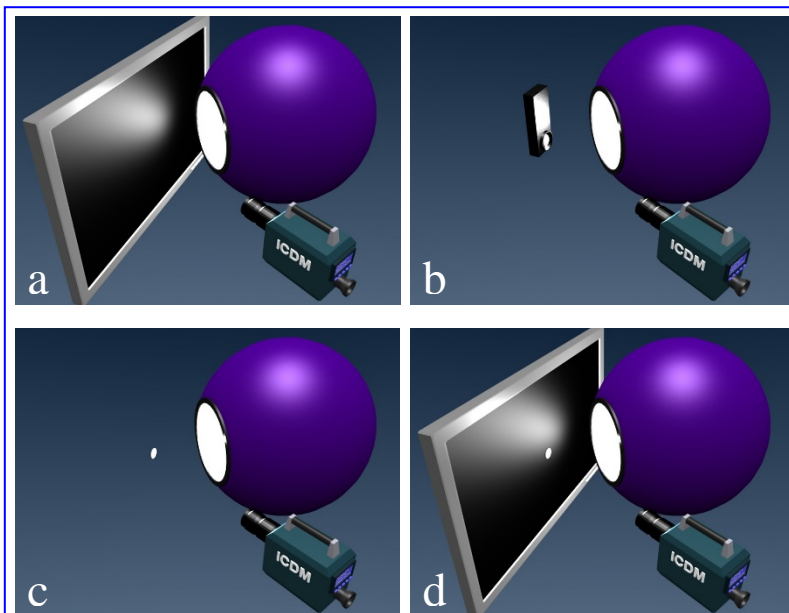


Fig. 10. Method to measure illuminance in place by calibrating a thin matte spectrally flat white (or gray) reflection target.



the display. We measure its luminance L_{trg} and record the monitor photocurrent J_{trg} , which may be the same as J_{cal} . We then have a luminance factor β_{trg} for our thin white target for use in this particular geometry given by

$$\beta_{\text{trg}} = \frac{\pi L_{\text{trg}} J_{\text{cal}}}{E_{\text{cal}} J_{\text{trg}}}. \quad (15)$$

In many cases the ratio $J_{\text{cal}}/J_{\text{trg}} = 1$. In Fig. 10d we show the small thin white target on the face of the display to measure the illuminance E_{off} by measuring the target luminance L_{off} with the display showing black or off and recording the photocurrent J_{off} .

$$E_{\text{off}} = \frac{\pi L_{\text{off}}}{\beta_{\text{trg}}} = \chi_{\text{cal}} J_{\text{off}}, \text{ where } \chi_{\text{cal}} = \frac{\pi L_{\text{off}}}{\beta_{\text{trg}} J_{\text{off}}}. \quad (16)$$

Here, χ_{cal} is the calibration of the photopic photodiode monitor that allows us to determine the illuminance from the photodiode current without the little target in place in order to provide a redundancy check on the illuminance measurement using the target. The target is removed for the luminance measurement of the display. The target is small enough to, hopefully, not perturb the measurement results. Note that this calibration of the white target is *ONLY* good for this specific source-detector-display geometry. The target needs to be spectrally flat for radiometric measurements and it needs to be opaque.

Ring-Light Source: Because the ring-light will not be affected by what is on the display, the display can be removed, and a cosine-corrected illuminance meter can determine the illuminance E_{ring} from the ring source. If an illuminance measurement is needed without moving the display, then a calibrated thin white target can be placed on the display surface, a measurement of the illuminance $E_{\text{trg-ring}}$ in Fig. 10b with the luminance $L_{\text{trg-ring}}$ in Fig. 10c is sufficient to calibrate the white target:

$$\beta_{\text{trg-ring}} = \pi L_{\text{trg-ring}} / E_{\text{trg-ring}}. \quad (17)$$

Then the illuminance E_{ring} under measurement conditions will be given by the luminance L_{trg} of the target on the display surface:

$$E_{\text{ring}} = \pi L_{\text{trg}} / \beta_{\text{trg-ring}}. \quad (18)$$

11.1.3.3 Collimated Sources

Collimated sources offer a beam of light with a relatively constant cross-section along its path. Caution, these can be very bright and eye protection may be required. As with the above uniform discrete source the illuminance and nonuniformity of the illuminance of such a beam can be measured using an illuminance meter that is of the correct size similar to the measurement fields shown in Fig. 9 relative to the beam diameter. White reflectance standards and other matte targets cannot be used for illuminance calibrations unless they have been calibrated specifically for the geometry employed by the measurement apparatus that is using the collimated source. The coverage of the collimated source must be larger than the measurement field of the LMD.

The advantage of using a collimated source over a discrete source (such as an integrating sphere exit port) is that it exhibits a uniform cross-section whereas a discrete source away from the normal of the display will exhibit an inverse-square nonuniformity across the measurement field on the display surface. Collimated sources keep the light confined to a beam whereas discrete sources tend to scatter the illumination over a wider area. Because of their parallel beams they work well in simulating the sun or moon independent of their beam widths (a particular size of beam is not required so long as it covers the measurement field with uniform illumination, preferably with a 1 % nonuniformity or less).

Collimated sources using quartz-tungsten-halogen bulbs may produce much heat and do damage to the display unless a heat absorbing filter is used to prevent IR from exiting the source. White LED lamps are finding use in collimated sources. Long-throw projectors and solar simulators may be found to be useful as collimated sources.

11.1.3.4 Converging Sources

Converging sources are often used in making BRDF measurements and examining matrix scatter. Caution, these can be very bright and eye protection may be required. In such cases relative measurements are often employed and a detector may not need to be calibrated. We cannot use white reflectance standards and other matte targets for illuminance calibrations unless they have been calibrated specifically for the geometry employed by the measurement apparatus that is using the converging source. If the source is too bright to allow a calibration of the source by an unfolded system, then it may be possible to use a calibrated black glass through which a calibration may be obtained.



11.1.4 NOTES

1. Exclusions: These measurement methods are not intended to deal with *detailed* measurements of special or strange reflection properties such as matrix scatter, photoluminescence, or retroreflection. Displays with narrow-band or strongly colored reflections can potentially be characterized by spectral reflectance or spectral reflectance factor measurements. Some special reflection and appearance properties are further covered by the ASTM Standards on Color and Appearance.¹

2. Spectral or Photometric Measurements: We will use the convention where spectral measurements have an explicit wavelength dependence, such as spectral radiance $L(\lambda)$, and photometric measurements do not, such as luminance L . For photometric measurements the light source spectra may need to be carefully chosen to simulate the typical application environment in order to achieve measurement accuracies approaching 1 %. *Spectral Measurements:* A spectroradiometer with a maximum bandwidth of 10 nm should be used for radiance measurements unless narrow-band illumination is present in significant quantity in which case it may be better to use a 5 nm bandwidth or smaller. A spectral irradiance meter with a maximum bandwidth of 10 nm should be used for irradiance measurements.

3. Display Orientation: Some of the ambient performance metrics can be affected by the orientation (i.e., rotation) of the display due to the dependence on viewing direction or the pattern presented on the display if luminance loading is significant. Therefore, the display darkroom and reflection measurements should be conducted at the orientation and pattern appropriate for the intended application.

4. Displayed Color: This chapter also assumes that the display will have different reflection coefficients when the display is at the lowest gray level (black) or at its maximum gray level (white). Thus, a separate reflection measurement may be required for each color state. If it can be shown that the reflection coefficients do not depend on the display's color state, then the reflection measurements need only be performed at the lowest gray level (black). The same applies to the transmission coefficients of transmissive displays. If the display has different transmission coefficients when the display is at its lowest gray level (black = shuttered) or its maximum gray level (white = transparent) then separate transmission measurements are required for each color state. If it can be shown that the transmission coefficients are independent of the display color state then the transmission measurements need only be performed at the highest gray level (white = transparent).

5. Illumination-Detection Geometry: The measurement results for the reflection parameters depend strongly upon the geometry of the illuminating source and the display. Various recommended geometries are specified in this chapter. The chosen illumination configuration or surround should be based on the intended application of the display. Outdoor and indoor applications can have both hemispherical diffuse and directed illumination components. The incident angle of the light source and viewing direction of the detector should also mimic the expected conditions under use.

6. Black and White: In the following sections we refer to black and white in some of the methods. In the event that a display doesn't have a "black" and a "white" then please allow these terms to refer to the minimum gray level for black and the maximum gray level for white. Picky, aren't we!

7. Lambertian vs. Diffuse: The term "diffuse" means scattered out of the specular direction. The term "Lambertian" means a uniform diffuser and is a type of diffusion (see the appendix B17 Reflection and Transmission Models & Terminology). "Diffuse" does NOT mean "Lambertian"!

8. Canonical Reflection Terminology: See the Tutorial Appendix B17 Reflection and Transmission Models & Terminology for further details.

9. Daylight, Sunlight, and Skylight Conditions: In order to define terminology in this document the following definitions will hold in describing ambient conditions as for ambient contrast and readability:

a. Sunlight: Direct sunlight falling on the surface of the display. We will assume $E_{\text{sun}} \cong 100\,000$ lx illuminance that is projected at an angle θ from the normal so that the illuminance on the screen is $E_{\text{sun}} \cos \theta$. Often we use a value of $\theta = 45^\circ$.

b. Skylight: Light from the sky, clouds, ground, etc., but not directly from the sun. We will assume $E_{\text{sky}} = 10\,000$ lx to 15 000 lx.

c. Daylight: This is a combination of skylight and direct sunlight: $E_{\text{day}} = E_{\text{sky}} + E_{\text{sun}} \cos \theta$.

Thus, to claim a daylight ambient contrast or daylight readability, the reflection parameters must be measured with a uniform source simulating the skylight and with a collimated or small directed source (collimated preferred) simulating the sunlight. The reflected luminances are then scaled to these illuminance levels.

PLEASE ESPECIALLY NOTE:

10. Measurements in Concert: Any individual measurement with a single apparatus in this chapter is not adequate for a complete characterization of reflection, for system validation, or for correlation with user experience. To fully accomplish such purposes, in general, these reflection metrics must be used in combination and/or along with other measurement methods.

¹ ASTM Standards on Color and Appearance Measurement, 8th edition (2008).



11.1.5 REFLECTION PARAMETERS

Reflectance Factor, Luminance Factor, Reflectance and Spectrally Resolved Measurement Results: In *all* cases of reflection measurements, the geometry of the apparatus must be specified. In this chapter we include a number of geometries to be used in making reflection measurements. In some cases, different reflection parameters can be reported, such as reflectance factor, luminance factor, and reflectance (as well as their spectrally resolved counterparts, spectral reflectance factor, radiance factor, and spectral reflectance). In reporting the reflectance factor, it is always necessary to include in the measurement documentation the acceptance cone of the detector as well as its placement and measurement field. In reporting a luminance factor result, it is assumed that the size of the acceptance cone (or angular aperture) and the size of the measurement field is not important in the result obtained (often the case in making hemispherical reflectance measurements, for example). For uniform hemispherical illumination, the luminance factor is the same as the diffuse reflectance (by virtue of Helmholtz reciprocity). Without making spectrally resolved measurements, we can expect uncertainties of a few percent to 10% (perhaps even more) when comparing results between laboratories and very different light sources, unless the spectrum of the light source is replicated accurately in each laboratory. Thus, the names of the measurements often use the general term “reflection” instead of a more specific reflection parameter term because different parameters can often be reported.

Consider the measurement example in Fig. 11 where the display does not have a specular or Lambertian component, but only a haze component. In all cases of reporting reflection parameters, the geometry must be reported. Here the detector is 30° to the left of normal and the source is 45° to the right of normal. The center of the source is 150 mm away from the center of the screen. The source is Lambertian with an exit port of 150 mm and nonuniformity of 1 %. The detector’s lens has a diameter of 35 mm and there is 400 mm from the front of the lens to the center of the screen; so we will call the detector distance to be 400 mm and assume that all the light entering the 35 mm diameter lens is being measured so that the acceptance area (entrance pupil) of the detector is 35 mm in diameter (this is not always a good assumption, but without more information from the manufacturer it is the best we can do).

Which reflection parameters might we be able to measure? We cannot measure the diffuse reflectance because we would not be collecting all the light that is diffused. We could measure something like a specular reflectance, at least in name only, because the source is wide enough so that the specular line from the detector reflected off the screen will intercept the source. However, a specular-configuration measurement might be very uncertain because of the haze. We could also measure the luminance factor (radiance factor) and reflectance factor (spectral reflectance factor). The “specular reflectance” (not really legitimate, but useful in some cases) would be recorded as the ratio of the measured luminance L to the source luminance L_s : $\rho_s = L/L_s$. Both the luminance factor and reflectance factor are given by $\pi L/E$ where L is the measured luminance and E is the measured illuminance. The difference between the reflectance factor and the luminance factor is that we must define the cone of detection for the reflectance factor, which would require our knowledge of the acceptance area diameter of the lens and the size of the measurement field in addition to all the other geometrical

configurations parameters that would be specified for the luminance factor. Note that for this kind of an apparatus geometry a small thin calibrated white target could be used to determine the illuminance.

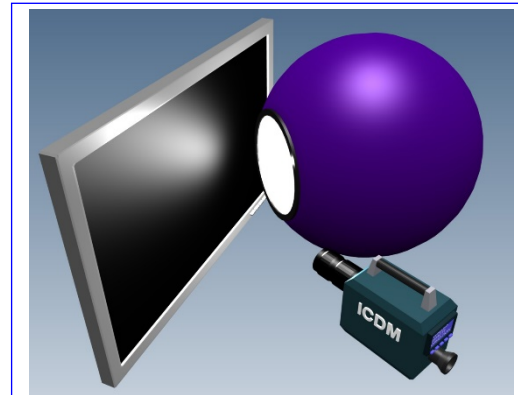


Fig. 11. Reflection measurement example to illustrate different reflection parameter that can be measured.

REFLECTANCE FACTOR				LUMINANCE FACTOR or SPECULAR REFLECTANCE			
Detector Geometry				Detector Geometry			
Distance from screen center	c_d	400	mm	Distance from screen center	c_d	400	mm
Angle from normal	θ_d	-30	°	Angle from normal	θ_d	-30	°
Measurement field	m_α	17	mm	Source Geometry			
Acceptance area diameter	D_d	35	mm	Distance from screen center	c_s	150	mm
Source Geometry				Angle from normal	θ_s	45	°
Distance from screen center	c_s	150	mm	Diameter of source	D_s	150	mm
Angle from normal	θ_s	45	°	Color	Q	K	
Diameter of source	D_s	150	mm	Illuminance from source	E	2360	lx
Color	Q	K		Luminance of sample	L	31.7	cd/m ²
Illuminance from source	E	2360	lx	Luminance Factor ($\beta = \pi L/E$)	β_K	0.0422	-
Luminance of sample	L	31.7	cd/m ²	Luminance of Source	L_s	9432	cd/m ²
Reflectance Factor ($R_K = \pi L/E$)	R_K	0.0422	-	Specular (regular) Reflectance	ρ_s	0.0382	-

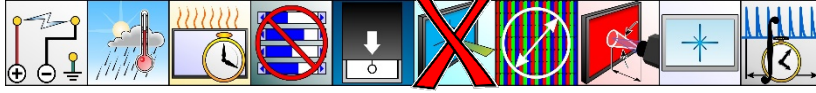


11.2 HEMISPHERICAL REFLECTION SPECULAR INCLUDED

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) of a display at a detector inclination angle of 8° ($-0^\circ + 2^\circ$) with the display exhibiting a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under uniform diffuse illumination provided by an integrating sphere. **Units:** none;

Symbol: $R_{di/8}$, $\rho_{8/di} = \beta_{di/8}$, $R(\lambda)_{di/8}$, $\beta(\lambda)_{di/8}$, etc..

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The display is placed at the center of the integrating sphere with its surface vertical. Note the orientation (e.g., landscape or portrait). The sphere lamp must have reached stability. The detector views the display through a hole in the wall of the sphere at an angle $\theta_d = 8^\circ$ ($-0^\circ + 2^\circ$) from the display surface normal (the display can be rotated inside the sphere). The detector is focused on the display surface. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

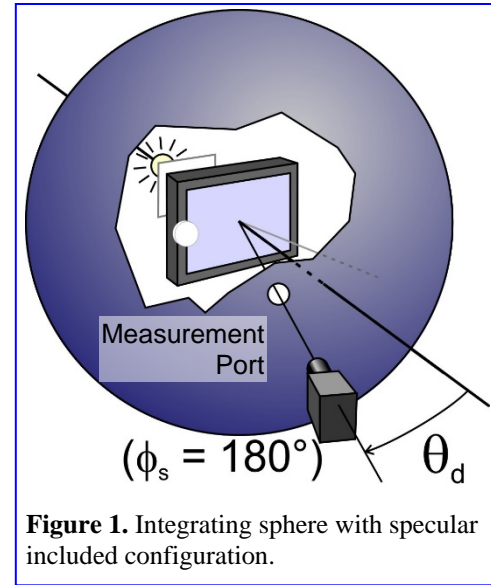


Figure 1. Integrating sphere with specular included configuration.

PROCEDURE: Exhibit the desired color Q on the display surface.

1. Measure the luminance L_{Qon} at the center of the display with the lamp illuminating the interior of the sphere (surround on).
2. Align the detector to the center of the reflectance standard and measure its luminance L_{stdQon} with the lamp illuminating the interior of the sphere. (Alternatively, record the illuminance E_{Qon} .)
3. Shutter the lamp so it does not illuminate the sphere interior (surround off). This may be accomplished by turning off the light source, but there will be a warmup time required if turned on again. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned off by disconnecting at the light source side so that the sphere interior conditions and performance are not changed. This step is not needed for reflective displays.
4. Measure the luminance $L_{stdQoff}$ of the reference standard with the lamp shuttered off. This luminance is zero for reflective displays. (Alternatively, record the illuminance E_{Qoff} .)
5. Align the detector to the center of the display and measure its luminance L_{Qoff} . This luminance is zero for reflective displays.

ANALYSIS: The reflectance $\rho_{8/di}$ and luminance factor $\beta_{di/8}$ (both with specular included) are given by

$$\rho_{Q8/di} = \beta_{Qdi/8} = \rho_{std} \frac{[L_{Qon} - L_{Qoff}]}{[L_{stdQon} - L_{stdQoff}]} = \pi \frac{[L_{Qon} - L_{Qoff}]}{[E_{Qon} - E_{Qoff}]} \quad (1)$$

Here, E_{Qon} and E_{Qoff} are the illuminances as measured by an illuminance meter, if employed. For reflective displays L_{Qoff} , $L_{stdQoff}$, and E_{Qoff} will be zero.

REPORTING: Report the size of the integrating sphere, inclination angle θ_d of the detector, the orientation of the display, the CCT of the source, and the calculated reflectance or luminance factor, $\rho_{di/8} = \beta_{di/8}$, of the display (or other appropriate reflection parameter as required).

COMMENTS: (1) **Other Configurations:** A number of configurations can also be used instead of an integrating sphere such as a hemisphere or sampling sphere. These cases will be covered in the subsequent subsections. (2) **Uniformity of Surround Luminance:** It is most important that the sphere wall have a relatively uniform luminance distribution over the sphere wall that is in the vicinity ($\pm 30^\circ$) of the specular direction. (3) **Sphere Diameter:** The sphere diameter should be no less than four (preferably from four to seven) times the largest outer dimension of the display. For large displays, a sampling sphere should be considered. (4) **Measurement Port Diameter:** The measurement port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example	
Display luminance with surround on L_{Qon} (cd/m ²)	447
Display luminance with surround off L_{Qoff} (cd/m ²)	254
Reference standard luminance with surround on L_{stdQon} (cd/m ²)	2166
Reference standard luminance with surround off $L_{stdQoff}$ (cd/m ²)	4.5
Known ρ_{std}	0.97
Calculate $\rho_{8/di} = \beta_{di/8}$	0.0866



entrance pupil of the detector and the measurement field should be smaller than the measurement port diameter. **(5) Detector Distance:** The detector should be moved back from the measurement port so that none of the bright interior illuminates the detector directly (if you see any of the white interior of the sphere or bright display bezel in the viewfinder of the detector then the luminance measurements can be corrupted by veiling glare). **(6) Robustness:** If the display's reflection properties are completely unknown, the hemispherical reflection measurement with specular included is the most general and robust measurement that can be made. **(7) Radiometric Measurements:** For greatest accuracy and flexibility, we recommend that you consider making spectrally resolved measurements and calculating the spectral reflection parameters—see comments in the introduction to this chapter. **(8) Lamp Light Source:** A broadband light source with a continuous spectral power distribution should be used. We recommend using a stabilized quartz-tungsten-halogen (QTH) lamp. To avoid heating the interior of the sphere (and the display), it is recommended that the lamp be external to the sphere and its housing fan cooled. Particularly if you are making spectrally resolved measurements, an additional external infrared blocking filter (e.g., KG-3 glass filter) may be used to reduce the infrared radiation entering the sphere as well as reduce the red content of the spectrum. If reflection measurements are performed on emissive displays, the lamp flux needs to be sufficiently high such that the reflected light signal is easily measurably over that from the display emission.

11.2.1 LARGE-ANGLE IMPLEMENTATION

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) at a selected angle greater than 8° of a display with a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) screen under uniform diffuse hemispherical illumination with the specular component included. **Units:** none; and **Symbol:** $R_{di/\theta}$, $\rho_{\theta/di} = \beta_{di/\theta}$, $R(\lambda)_{di/\theta}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle θ_d from the display surface normal (or tilt the display inside the surround), where $8^\circ \leq \theta_d \leq 85^\circ$.

Surround: For variable detector inclination angles θ_d , an in-plane slot with a defined measurement port opening may be used to implement the variable inclination angle. However, to minimize sphere non-uniformities, the slot area beyond the port opening should be covered and have the same reflectance as the rest of the sphere interior wall. A slotted sphere is one example of how this large-angle method can be implemented with a sampling sphere.¹

PROCEDURE: Same as main section.

ANALYSIS: Same as main section.

REPORTING: Same as main section.

¹ D. Hertel, E. F. Kelley, "Viewing Direction Measurements with Hemispherical Diffuse Illumination on E-Paper Displays," SID Digest 45: 532–535 (2014).



11.2.2 SAMPLING-SPHERE IMPLEMENTATION

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) of a display at an 8° detector inclination angle, using a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) screen, under uniform diffuse hemispherical illumination with the specular component included.

The sampling sphere is a useful apparatus for obtaining uniform hemispherical diffuse illumination for large displays that cannot realistically be placed within an integrating sphere.

Units: none; and **Symbol:** $R_{di/8}$, $\rho_{8/di} = \beta_{di/8}$, $R(\lambda)_{di/8}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle of $\theta_d = 8^\circ$ ($-0^\circ + 2^\circ$) from the display surface normal.

Surround: The display surface should be placed as close as possible to the inner white surface of the sphere. If the emitting surface of the display is significantly recessed from the front surface of the display, then the sphere sample port size is important: For a 1 % introduced error the ratio of the diameter D_{sp} of the sample port to the recess depth h should be $D_{sp}/h = 8$; for a 0.1% introduced error, $D_{sp}/h = 16$. Care should be taken to avoid putting excessive pressure on the display surface. A small port with a diffuser and detector may be useful to monitor the stability of the source during the measurement. Be sure that the detector is far back from the measurement port so that the measurement results are not affected by the bright surround of the sample port. Be sure that the measurement field is centered in the measurement port. Also to be avoided in the measurement is any vignette shadowing near the round edge of the sampling port that arises from its thickness.

Illuminance

Measurement: The illuminance (or spectral irradiance) on the display can be determined by measuring the interior sphere wall

adjacent to the sample port. The wall reflectance factor ρ_{wall} of that interior wall location can be determined by comparing the luminance L_{wall} (or spectral radiance) of the wall with that of a calibrated white standard placed at the sample port:

$\rho_{wall} = \rho_{std} L_{wall} / L_{std}$, where L_{std} is the luminance measured from the white standard in the plane of the sample port. The same relationship is also used for spectral measurements. The illuminance might also be measured using a photopic

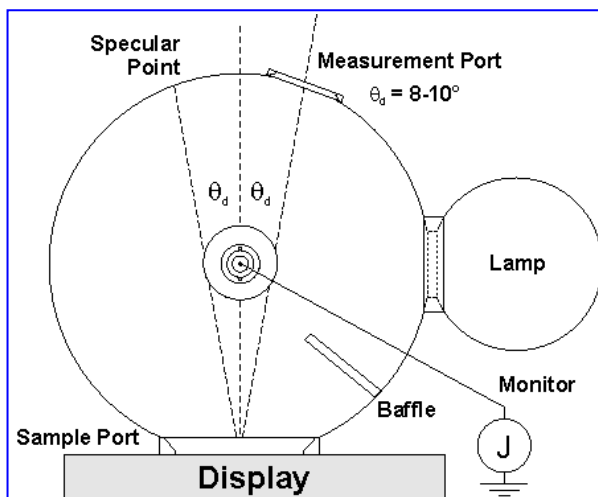


Fig. 1. Sampling sphere with specular included configuration. A detector with photocurrent J monitors the sphere illuminance. This is for illustration purposes and does not suggest actual sizes or configuration to be used for this apparatus.

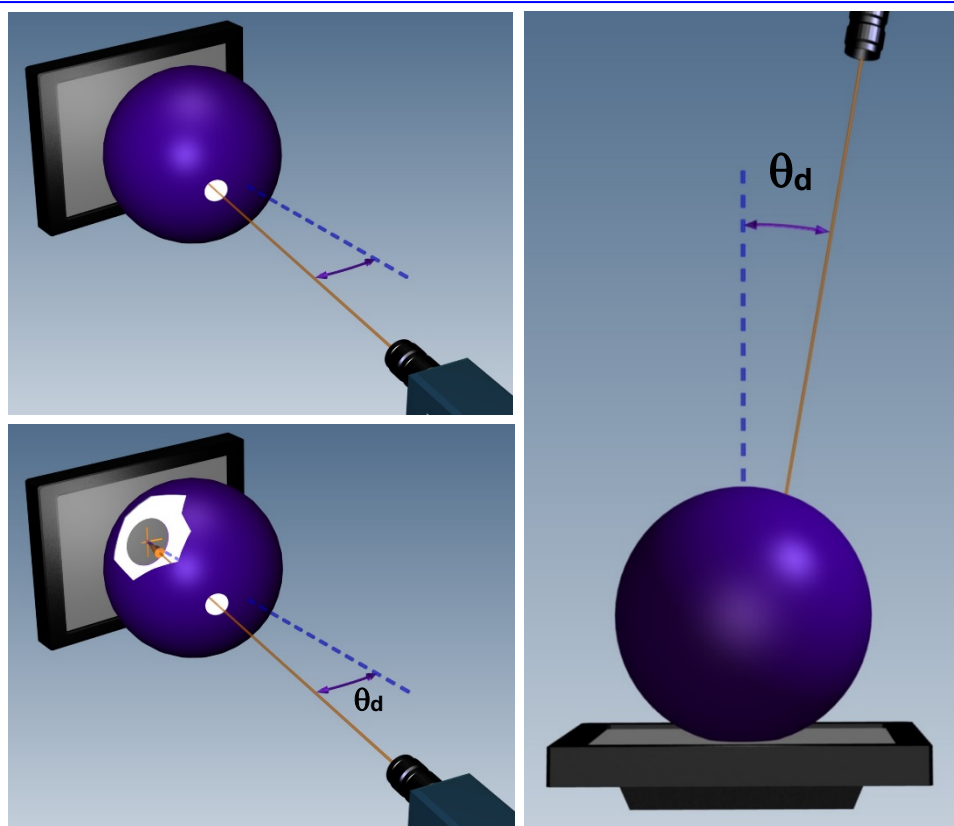


Fig. 2. Sampling-sphere illustrations. The dashed blue line is the display normal.



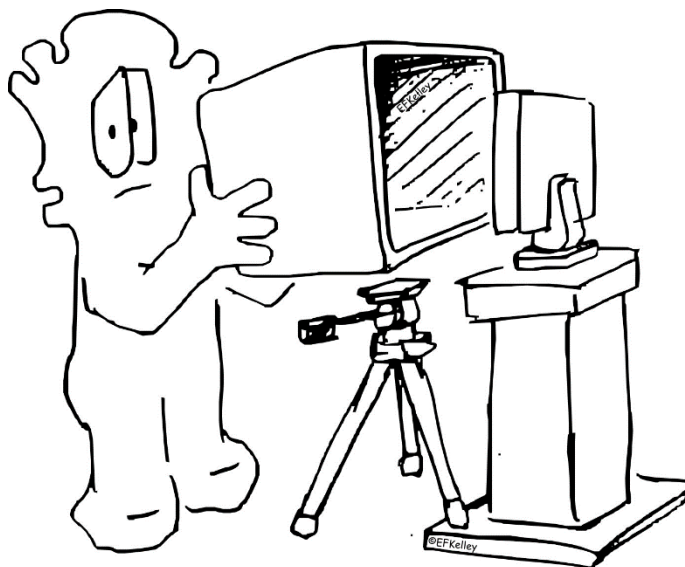
photodiode. We will assume a wall luminance measurement here. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

PROCEDURE (PHOTOMETRIC):

1. Turn ON the display to the desired color field and place it against the opening of the sphere sample port at the desired orientation relative to the detector. Turn ON the sphere lamps and allow lamps and display emission to stabilize.
2. Measure the luminance L_{Qon} at the center of the display color pattern with the hemispherical surround ON.
3. Align the detector to the calibrated interior wall location of the sampling sphere adjacent to the sample port and measure the luminance $L_{wallQon}$ from the sphere wall.
4. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
5. Measure the luminance $L_{wallQoff}$ of the reference standard with the hemispherical surround OFF and the display with it's color state ON. Values are zero for reflective displays.
6. Align the detector to the center of the display's color pattern and measure its luminance L_{Qoff} with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main section, except that ρ_{wall} is used in Equation (1) instead of ρ_{std} , and all the $L_{std}...$ luminances are replaced by $L_{wall}...$

REPORTING: Same as main section.



You might be a Rustic if you use a beer cooler as an integrating sphere.

RUSTIC METROLOGY



11.2.3 HEMISPHERICAL ILLUMINATION IMPLEMENTATION

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) of a display with a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) screen under uniform-diffuse hemispherical illumination with specular included. The hemispherical illumination can be realized by using a hemisphere. **Units:** none; and **Symbol:** $\rho_{0/di} = \beta_{di/\theta}$, etc.

ADDITIONAL SETUP: The same guidelines and precautions stated in the main integrating sphere section apply to this section, except as specifically noted here: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The display surface should be placed at the center of the hemisphere. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at a fixed inclination angle of $\theta_d = 8^\circ$ ($-0^\circ + 2^\circ$) from the display surface normal, or at a variable inclination angle where $8^\circ \leq \theta_d \leq 85^\circ$.

Surround: The hemisphere geometry is generally less uniform than a full integrating sphere or sampling sphere. It is important that symmetric diffuse lighting is used to improve the uniformity of the hemispherical illumination on the display. It is also important that the illumination on the hemisphere wall be uniform within $\pm 30^\circ$ of the specular direction.

Illuminance Measurement: Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements. If a white reflectance standard or target is employed to provide a measurement of the illuminance, it is critical that the illuminance is uniform across the display and standard (or target). A measurement of a calibrated white standard, target, or wall is assumed below as ρ_{std} .

PROCEDURE (PHOTOMETRIC): Same as the main integrating sphere section for an open base hemisphere. Use the following procedure for the closed base hemisphere:

1. Turn ON the display to the desired color field and place it at the mechanical center of the hemisphere in the desired orientation relative to the detector. Turn ON the hemisphere lamps and allow lamps and display emission to stabilize.
2. Measure the luminance L_{Qon} at the center of the display color pattern with the hemispherical surround ON.
3. Align the detector to the calibrated interior wall location of the hemisphere adjacent to the sample port and measure the luminance L_{stdQon} from the wall.
4. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
5. Measure the luminance $L_{stdQoff}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
6. Align the detector to the center of the display's color pattern and measure its luminance L_{Qoff} with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main integrating-sphere section if the hemisphere has an open base. If the hemisphere has a closed base and a base wall measurement is used to determine the illuminance, then the analysis is the same as the main section, except that ρ_{wall} is used in Eq. (1) instead of ρ_{std} and all $L_{std}...$ are replaced with $L_{wall}...$

REPORTING: Same as main section.

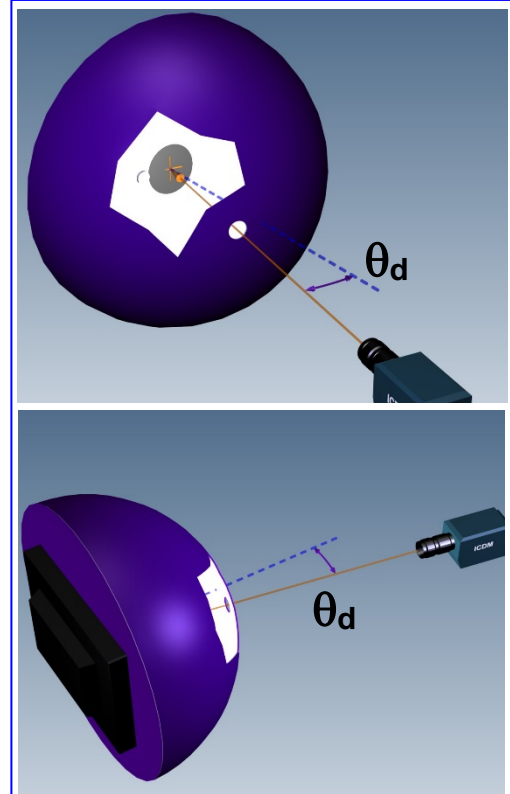


Fig. 1. Hemisphere with specular included configuration. The blue dashed line is the display normal.



11.3 HEMISPHERICAL REFLECTION SPECULAR EXCLUDED

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present. Take care to ensure that the display is oriented properly, i.e., that the display normal bisects the angle between the LMD port and the specular port.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) with specular excluded of a display at an 8° detector inclination angle with a selected screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under uniform diffuse hemispherical illumination. **Units:** none; and **Symbol:**

$\rho_{0/de} = \beta_{de/0}$, etc.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Uniform hemispherical diffuse light is needed to illuminate the screen from all but the specular direction. The display is placed at the desired orientation in the center of the sphere. The detector is aligned to view the center of the display surface through a hole in the illuminating surround at an angle of $\theta_d = 8^\circ$ (-0° to $+2^\circ$) from the display surface normal (or tilt the display inside the surround). The detector is focused on the display surface if no specular image is available (no specular component of reflection); if a distinct virtual image of the specular port is visible, then focus on the specular-port image.

Surround: An integrating sphere is the best configuration to use for hemispherical diffuse reflection measurements. A number of configurations can also be used, such as a hemisphere or sampling sphere. These cases will be covered in the subsequent sub-sections. In all cases, it is most important that the surround have a uniform illuminance distribution over the part of the surround that is in the vicinity ($\pm 30^\circ$) of the normal of the display surface. The sphere diameter should be no less than four to preferably seven times the outer dimension of the display. For large displays, a sampling sphere should be considered. The measurement port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the entrance pupil of the detector. The detector should be moved back from the hole so that only a fraction of the screen is visible to the detector to avoid stray light from the bright interior of the sphere.

Specular Light Trap: If the specular port doesn't open into a large darkroom, a light trap may be needed to provide a black specular port and not reflect any light coming out the specular port. This may be accomplished with a gloss trap—see the appendix A13.1.4 Cone Light Trap. It is recommended that the angular subtense of the specular port from the center of the display should be $\leq 8^\circ$, and the port diameter should be $< 20\%$ the sphere diameter.

The measurement results can be very sensitive to the reflection properties of the display. Displays with nontrivial mirror-like specular components should work well with the specular excluded geometry. However, displays that have a significant haze component or matrix-scatter component will be sensitive to size of and distance to specular port. Figure 2 illustrates that, unlike specular reflection, the image of the specular port for a display with significant haze is fuzzy. Therefore, aligning the detector to the specular angle can be difficult, and the measurement result can be very sensitive to the size of the measurement field and the alignment. In addition, light from the perimeter of the specular port may contribute to veiling glare in the detector. Because of these issues, specular excluded measurements on displays with significant haze should be avoided.

Illuminance measurement: Often we use a white reflectance standard to measure the illuminance and will be assumed below. A calibrated white target may also be used. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: A broadband light source with a continuous spectral power distribution should be used. We recommend using high intensity quartz-tungsten-halogen (QTH) lamps stabilized to less than $\pm 1\%$ per hour of operation. If reflection measurements are performed on emissive displays, the lamp intensity needs to be sufficiently high such that the reflected light signal is significantly larger than the darkroom luminance of the display. Be careful of heating the display when using

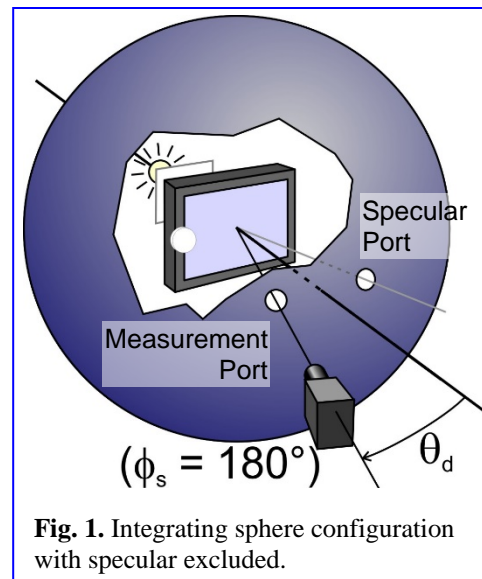


Fig. 1. Integrating sphere configuration with specular excluded.

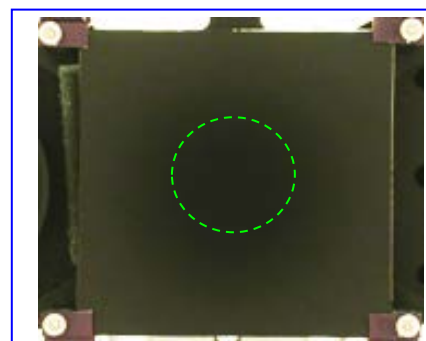


Fig. 2. LMD view of haze sample with specular port in specular direction. Dashed circle represents potential measurement area.



QTH lamps. When the light is projected into the sphere a cooled IR blocking filter can dramatically reduce the heating at a cost of a reduction in the reddest part of the spectrum. White LEDs are finding applications as lamp sources as well.

PROCEDURE:

1. Place the display in the center of the sphere at the desired orientation. Turn ON the display in the integrating sphere to the desired color pattern. Turn ON the integrating sphere and allow lamps and display emission to stabilize.
2. Carefully align the detector at the desired viewing direction θ_d , so the measurement area is centered within the specular image of the specular port. If no distinct image is visible, a thin reflective mirror or film can be temporarily placed on the display surface for detector alignment. Alignment marks or aids should be used to register this detector orientation, since the detector will need to alternate between the specular direction and the white standard.
3. Measure the luminance L_{Qon} at the center of the display color pattern with the hemispherical surround ON.
4. Align the detector to the center of the reflectance standard and measure its luminance L_{stdQon} with the surround and display ON.
5. Turn OFF the integrating sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the sphere interior conditions, and performance are not changed. This step is not needed for reflective displays.
6. Measure the luminance $L_{stdQoff}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
7. Align the detector to the center of the display's color pattern and measure its luminance L_{Qoff} with the surround OFF. Values are zero for reflective displays.

ANALYSIS: The reflectance with specular excluded, $\rho_{de/\theta}$, is the same as the luminance factor with specular excluded, $\beta_{de/\theta}$, and is calculated using the known reflectance ρ_{std} of the white diffuse reflectance standard determined under the same spectral, geometric illumination, and detection conditions:

$$\rho_{Q\theta/de} = \beta_{Qde/\theta} = \rho_{std} \frac{[L_{Qon} - L_{Qoff}]}{[L_{stdQon} - L_{stdQoff}]} \quad (1)$$

For reflective displays, L_{Qoff} and $L_{stdQoff}$ will be zero.

Spectral Measurements: The spectral radiance factor $\beta_{de/\theta}(\lambda)$ analysis is analogous to Eq. (1) as illustrated in the introduction (11.1.2). In this case, spectral measurements may be made with an arbitrary spectrally smooth broadband source at the defined illumination/detection geometry, and the resulting luminous reflectance of the display can be calculated at the desired source spectra.

REPORTING: Report the details of the source-detector geometry and the reflection parameter that has been measured. If the reflectance factor has been measured, then be sure to report the geometric details of the cone of the detector.

COMMENTS: An assessment of the display's reflection properties would be valuable in determining if this specular-excluded measurement would be appropriate. If an observer holding the display can see a distinct virtual image off the display surface in the specular direction, then this a specular-exclusion measurement may be of value. However, if the virtual image is completely fuzzy, then this measurement will not be robust and should be avoided. In addition, if the reflection properties of the display are dependent on the size of the display pattern (for example full screen or center box), then the reflection measurement should be performed for the pattern of interest. To ensure measurement integrity, the reflected component of the hemispherical diffuse illumination should be much greater than the display emission, if possible [i.e., $L_{Qon}(\lambda) \gg L_{Qoff}(\lambda)$, with a luminance ratio of 2:1 or more is very helpful].

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Analysis example	
Display luminance with surround ON L_{Qon} (cd/m ²)	439
Display luminance with surround OFF L_{Qoff} (cd/m ²)	253
Reference standard luminance with surround ON L_{stdQon} (cd/m ²)	2155
Reference standard luminance with surround OFF $L_{stdQoff}$ (cd/m ²)	4.48
Known ρ_{std}	0.965
Calculate $\beta_{de/\theta}$.0834



11.3.1 LARGE-ANGLE IMPLEMENTATION (SPECULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) at a selected angle greater than 8° of a display with a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) screen under uniform-diffuse hemispherical illumination with the specular component excluded. **Units:** none; and

Symbol: $\rho_{\theta/de} = \beta_{de/\theta}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle of θ_d from the display surface normal (or tilt the display inside the integrating sphere), where $8^\circ \leq \theta_d \leq 85^\circ$. The specular port will be at the same in-plane angle in the specular direction.

Specular Light Trap: For variable detector inclination angles θ_d , an in-plane slot with defined measurement and specular port openings may be used to implement the variable inclination angle. However, to minimize sphere non-uniformities, the slot area outside the port openings should be filled with material of the same reflectance as the rest of the hemisphere interior wall.

PROCEDURE: Same as main section.

ANALYSIS: Same as main section.

REPORTING: Same as main section.

11.3.2 SAMPLING-SPHERE IMPLEMENTATION (SPECULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) at an angle $\theta_d = 8^\circ$ ($-0^\circ + 2^\circ$) of a display with a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) screen under uniform-diffuse hemispherical illumination with the specular component excluded. **Units:** none; and **Symbol:** $\rho_{\theta/de} = \beta_{de/\theta}$, etc.

The sampling sphere is a useful apparatus for obtaining uniform hemispherical diffuse illumination for large displays that cannot realistically be placed within an integrating sphere.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at an angle of $\theta_d = 8^\circ$ ($-0^\circ + 2^\circ$) from the display surface normal. A specular port is placed on the other side of the normal at the same angle as θ_d .

Surround: The display surface should be placed as close as possible to the inner white surface of the sphere. If the emitting surface of the display is significantly recessed from the front surface of the display, then the sphere sample port size is important: For a 1 % introduced error the ratio of the diameter D_{sp} of the sample port to the recess depth h should be $D_{sp}/h = 8$; for a 0.1% introduced error, $D_{sp}/h = 16$. Care should be taken to avoid putting excessive pressure on the display surface. A small port with a diffuser and detector may be useful to monitor the stability of the source during the measurement. Be sure that the detector is far back from the measurement port so that the measurement results are not affected by the bright surround of the sample port. Be sure that the measurement field is centered in the measurement port. Also to be

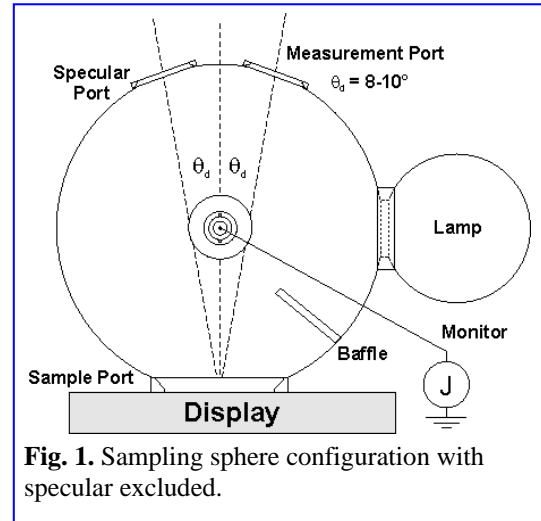


Fig. 1. Sampling sphere configuration with specular excluded.



avoided in the measurement is any vignette shadowing near the round edge of the sampling port that arises from its thickness. A slotted sphere is one example of how this large-angle method can be implemented with a sampling sphere. ¹

Illuminance Measurement: The illuminance (or spectral irradiance) on the display can be determined by measuring the interior sphere wall adjacent to the sample port. The wall reflectance factor ρ_{wall} of that interior wall location can be determined by comparing the luminance L_{wall} (or spectral radiance) of the wall with that of a calibrated white standard placed at the sample port: $\rho_{\text{wall}} = \rho_{\text{std}} L_{\text{wall}} / L_{\text{std}}$, where L_{std} is the luminance measured from the white standard in the plane of the sample port. The same relationship is also used for spectral measurements. The illuminance might also be measured using a photopic photodiode. We will assume a wall luminance measurement here. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

PROCEDURE (PHOTOMETRIC):

1. Turn ON the display to the desired color field and place it against the opening of the sphere sample port at the desired orientation relative to the detector. Turn ON the sphere lamps and allow lamps and display emission to stabilize.
2. Carefully align the detector at the desired viewing direction θ_d , so the measurement area is centered within the specular image of the specular port. If no distinct image is visible, a thin reflective mirror or film can be temporarily placed on the display surface for detector alignment. Alignment marks or aids should be used to register this detector orientation, since the detector will need to alternate between the specular direction and the white standard.
3. Measure the luminance $L_{Q\text{on}}$ at the center of the display color pattern with the hemispherical surround ON.
4. Align the detector to the calibrated interior wall location of the sampling sphere adjacent to the sample port and measure the luminance $L_{\text{std}Q\text{on}}$ from the sphere wall.
5. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
6. Measure the luminance $L_{\text{std}Q\text{off}}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
7. Align the detector to the center of the display's color pattern and measure its luminance $L_{Q\text{off}}$ with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main section, except that ρ_{wall} is used in Equation (1) instead of ρ_{std} , and all the L_{std} luminances are replaced by L_{wall} .

REPORTING: Same as main section.

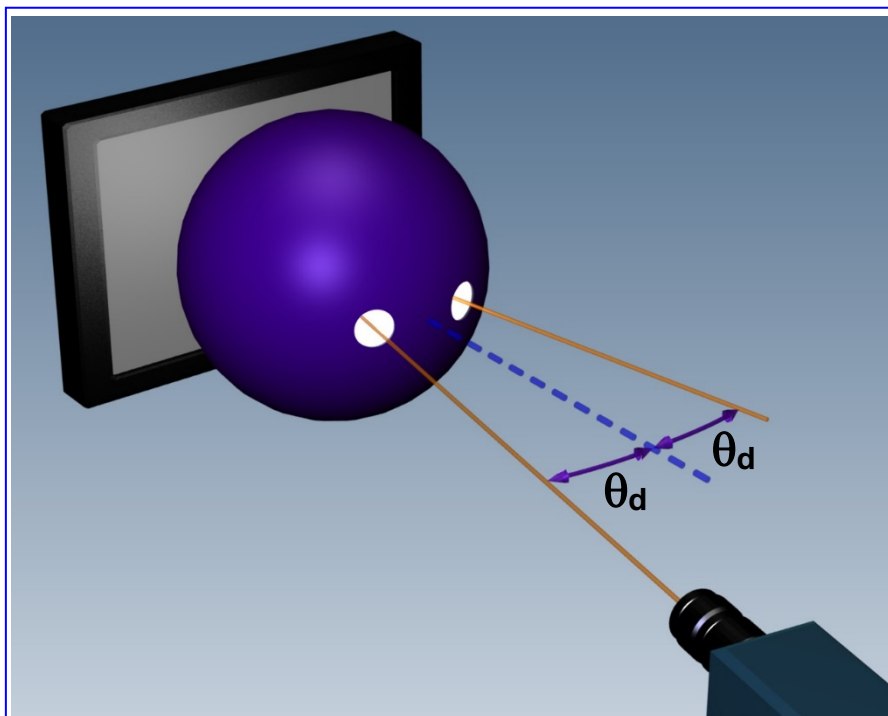


Fig. 2. Sampling sphere with specular excluded port opened.

¹ D. Hertel, E. F. Kelley, "Viewing Direction Measurements with Hemispherical Diffuse Illumination on E-Paper Displays," SID Digest 45: 532–535 (2014).



11.3.3 HEMISPHERE IMPLEMENTATION (SPECULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the reflection properties of the display and the size of the port used to exclude the specular component especially if nontrivial matrix scatter or haze is present.

DESCRIPTION: Measure an appropriate reflection parameter (reflectance factor, luminance factor, diffuse reflectance, and the spectral counterparts) with specular excluded of a display at a detector inclination angle of $\theta_d = 8^\circ (-0^\circ + 2^\circ)$ with a selected screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under uniform diffuse hemispherical illumination with the use of a hemispherical source apparatus. **Units:** none; and **Symbol:** $\rho_{\theta/de} = \beta_{de/\theta}$, etc.

ADDITIONAL SETUP: The following requirements are needed for this particular implementation of hemispherical illumination in addition to the setup conditions described in the main section. The display surface should be placed at the center of the hemisphere. The detector is aligned to view the center of the surface of the display through a hole in the illuminating surround at a fixed inclination angle of $\theta_d = 8^\circ (-0^\circ + 2^\circ)$ from the display surface normal, or at a variable inclination angle where $8^\circ \leq \theta_d \leq 80^\circ$. A specular port is placed on the other side of the normal at the same angle as θ_d .

Surround: The hemisphere geometry is generally less uniform than a full integrating sphere. It is important that symmetric diffuse lighting is used to improve the uniformity of the hemispherical illumination on the display.

Illuminance Measurement: Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements. If a white reflectance standard or target is employed to provide a measurement of the illuminance, it is critical that the illuminance is uniform across the display and standard (or target). A measurement of a calibrated white standard, target, or wall is assumed below as ρ_{std} .

PROCEDURE: Same as the main integrating sphere section for an open base hemisphere. Use the following procedure for the closed base hemisphere:

1. Turn ON the display to the desired color field and place it in the center of the hemisphere in the desired orientation relative to the detector. Turn ON the hemisphere lamps and allow lamps and display emission to stabilize.
2. Carefully align the detector at the desired viewing direction θ_d , so the measurement area is centered within the specular image of the specular port. If no distinct image is visible, a thin reflective mirror or film can be temporarily placed on the display surface for detector alignment. Alignment marks or aids should be used to register this detector orientation, since the detector will need to alternate between the specular direction and the white standard.
3. Measure the luminance L_{Qon} at the center of the display color pattern with the hemispherical surround ON.
4. Align the detector to the calibrated interior wall location of the hemisphere adjacent to the sample port and measure the luminance L_{stdQon} from the wall.
5. Turn OFF the sampling sphere hemispherical diffuse illumination. This may be accomplished by turning OFF the light source. If the sphere light is input by a portable source (like an optical fiber bundle), then the light can be turned OFF by disconnecting at the light source side so that the interior conditions and performance of the sphere are not changed. This step is not needed for reflective displays.
6. Measure the luminance $L_{stdQoff}$ of the reference standard with the hemispherical surround OFF and the display with its color state ON. Values are zero for reflective displays.
7. Align the detector to the center of the display's color pattern and measure its luminance L_{Qoff} with the surround OFF. Values are zero for reflective displays.

ANALYSIS: Same as main integrating sphere section if the hemisphere has an open base. If the hemisphere has a closed base and a base wall measurement is used to determine the illuminance, then the analysis is the same as the main section, except that ρ_{wall} is used in Eq. (1) instead of ρ_{std} and all $L_{std}...$ are replaced with $L_{wall}...$

REPORTING: Same as main section.

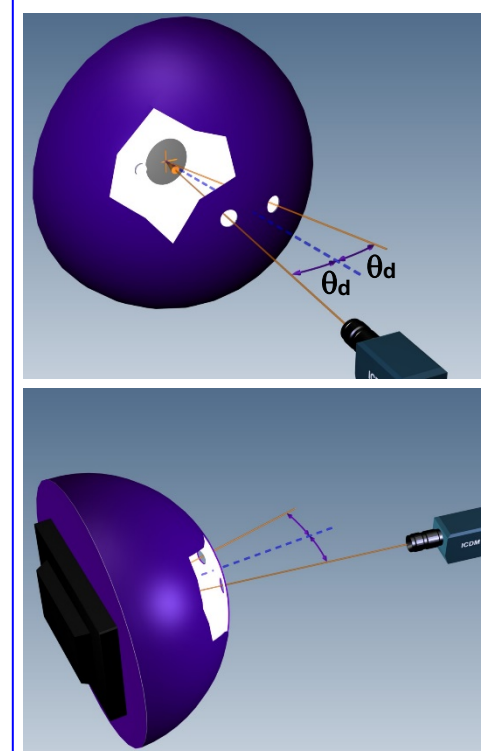


Fig. 1. Hemisphere configuration with specular excluded.



11.4 CONICAL REFLECTION SPECULAR INCLUDED

CAUTION: The implementation of this method using the conical design shown in Fig. 1 is no longer recommended unless the source can be made uniform. The source can have significant illumination nonuniformity, and the measurement results can be very sensitive to the display's reflection properties and the entire geometry of the apparatus.

DESCRIPTION: Measure an appropriate reflection parameter of a display screen with a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under conical illumination with the specular component included. The conical illumination geometry is intended only as an approximation for hemispherical illumination but does not extend over the entire 180° hemisphere above the place of the surface being measured. **Units:** none; and **Symbol:** $\beta_{\text{con-si}/\theta}$, $R_{\text{con-si}/\theta}$.

APPLICATION: All emissive or reflective direct-view displays. This type of reflection measurement may be useful for displays that will be deeply recessed as in a dashboard of an automobile or aircraft.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: A large subtense spherical cap with its circular edge placed a distance c_s from the display is used as an approximation for hemispherical diffuse light. The display surface should be parallel to the circular edge of the cap with the display normal centered within the spherical cap—see Fig. 1. An alternate implementation of the conical illumination can be an integrating sphere placed a distance c_s from the display surface—see Fig. 2. In either case, the detector is aligned to view the center of the display surface through a hole in the illuminating surround at an angle of θ_d from the display surface normal, where $8^\circ \leq \theta_d \ll \theta_c/2$ and where θ_c is the subtense of the spherical cap. The detector is focused on the display surface.

Surround: The degree to which the spherical cap or displaced integrating sphere can adequately approximate hemispherical illumination is dependent on the source subtense θ_c , the uniformity of the illumination, and the BRDF profile of the display. For example, if the display has an anti-glare surface with a strong haze profile out to $\pm 30^\circ$ relative to the specular direction, then the source subtense should be $\theta_c > 2(\theta_d + 30)$. It is most important that the surround have a relatively uniform illuminance distribution over the illumination angles where the display has a strong haze profile. In general, if the BRDF profile of the display is not known, it is recommended that the source have a subtense of $\theta_c \geq 130^\circ$. However, if the display has a nontrivial Lambertian-like reflection component that is sensitive to illumination over the entire hemisphere, then a full hemispherical illumination would be suggested if possible.

The measurement port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the entrance pupil of the detector. The detector should be moved back from the hole so that only a fraction of the screen is visible to the detector. For variable detector inclination angles θ_d , an in-plane slot with a defined measurement port opening may be used to implement the variable inclination angle. However, to minimize illumination non-uniformities, the slot area outside the port opening should be made of material with the same reflectance as the rest of the source interior wall.

Illuminance Measurement: The illuminance E on the display can be measured with a cosine-corrected illuminance meter. The display shall be replaced by the spectral irradiance or illuminance meter when performing this measurement, with the meter active area centered and at the same measurement plane. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

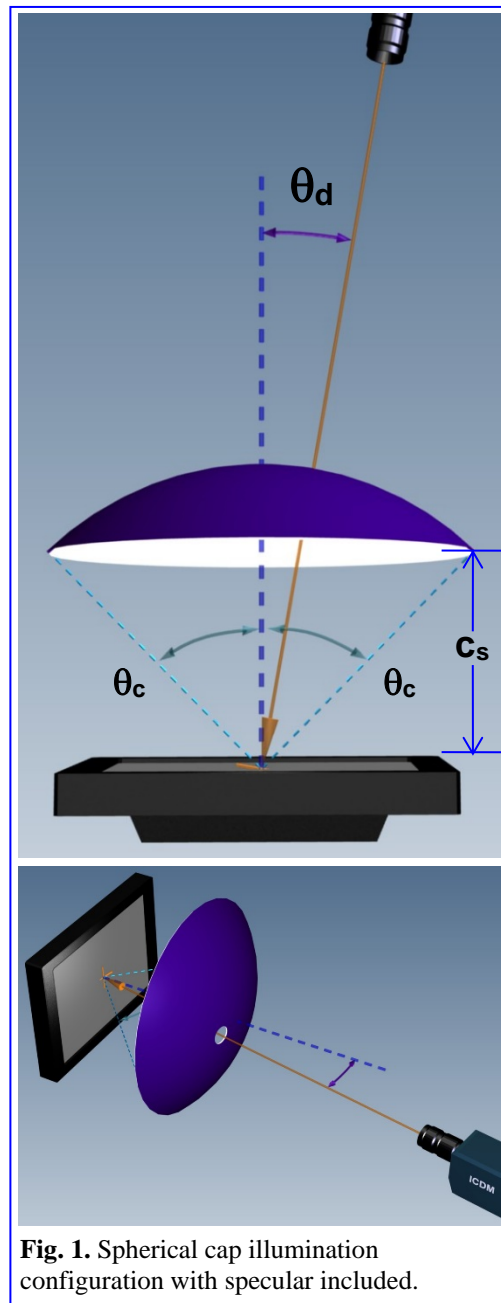


Fig. 1. Spherical cap illumination configuration with specular included.



Lamps: A broadband light source with a continuous spectral power distribution should be used. Quartz-tungsten-halogen (QTH) lamps stabilized to less than ± 1 % per hour of operation may be used. If reflection measurements are performed on emissive displays, the lamp intensity needs to be sufficiently high such that the reflected light luminance is significantly larger than the darkroom luminance of the display. Be careful of heating the display when using QTH lamps. A cooled IR blocking filter can dramatically reduce the heating at a cost of a reduction in the reddest part of the spectrum. White LEDs are finding applications as lamp sources as well.

PROCEDURE: This procedure accounts for light from the display influencing the illumination from the source. The source should be warmed up and stable. Illuminance measurements can be made either with a thin white target specially calibrated for this geometric configuration, made with a photopic photodiode, or made with a wall measurement of the source. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

1. Measure the luminance $L_{Qcon-si}$ of the display with the source turned ON. Determine the illuminance E_{Qon} on the display using a white target with luminance L_{trgQon} or some alternative method.
2. Measure the darkroom luminance L_{Qoff} at the center of the display color pattern with the source lamp OFF, either shutter the source lamp or turn it off. Record the illuminance E_{Qoff} or the luminance $L_{trgQoff}$ of the target.

ANALYSIS: The luminance factor $\beta_{con-si/\theta}$ with specular included is calculated using either the target luminance or the measured illuminance:

$$\beta_{Qcon-si/\theta} = \beta_{std} \frac{[L_{Qcon-si} - L_{Qoff}]}{[L_{stdQon} - L_{stdQoff}]} = \pi \frac{[L_{Qcon-si} - L_{Qoff}]}{[E_{Qon} - E_{Qoff}]} \quad (1)$$

where the numerator is the net reflected luminance from the display. For reflective displays, L_Q will be zero. Here β_{std} is the luminance factor of the white standard as used in this illumination geometry (remember, these white standards are not Lambertian).

REPORTING: Report the inclination angle θ_d of the detector, the orientation of the display, the type of surround used for illumination and the CCT of the source, the source distance c_s to the display, the illuminance on the display E_{Qon} , the calculated luminous factor $\beta_{con-si/\theta}$ of the display at the applied color and the corresponding CCT of the light source used in the calculation.

COMMENTS: If the reflection properties of the display are dependent on the size of the display pattern (for example full screen or center box), then the reflection measurement should be performed for the pattern of interest. If possible, to ensure measurement integrity, the reflected component of the diffuse illumination should be significantly greater than the display emission (i.e., $L_{Qcon-si} \gg L_{Qoff}$). No specific source distance and subtense are specified for this measurement. Facilities must agree on measurement parameters appropriate for their comparisons or for internal use in monitoring manufacturing processes.

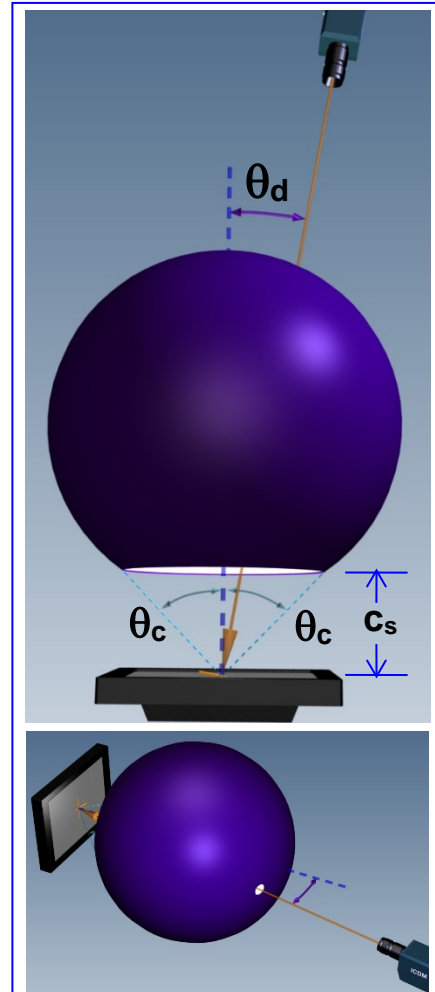


Fig. 2. Displaced integrating sphere illumination configuration with specular included.



11.4.1 CONICAL REFLECTION SPECULAR EXCLUDED

CAUTION: The implementation of this method using the conical design shown in Fig. 1 (left side) is no longer recommended unless the source can be made uniform. This measurement can have significant illumination non-uniformity and be very sensitive to the display's reflection properties. This measurement is not recommended for displays that exhibit haze or matrix scatter. Displays with Lambertian and/or specular reflection components should produce acceptable results if the illumination uniformity is good.

DESCRIPTION: Measure the spectral reflectance factor of a display with a selected screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under a conical illumination geometry with the specular component excluded. **Units:** none; and **Symbol:** $\beta_{\text{con-se}/\theta}$.

ADDITIONAL SETUP: A specular port is provided at angle θ_d on the opposite side of the normal. The detector is focused on the display surface if no distinct image of the specular port is visible, otherwise focus on the distinct image of the specular port.

PROCEDURE: Same as main section, except $L_{Q\text{con-se}}$ is used for the display measurement with the source on.

ANALYSIS: Same as main section, except $\beta_{\text{con-se}/\theta}$ is the resulting luminance factor.

$$\beta_{Q\text{con-se}/\theta} = \beta_{\text{std}} \frac{[L_{Q\text{con-se}} - L_{Q\text{off}}]}{[L_{\text{std}Q\text{on}} - L_{\text{std}Q\text{off}}]} = \pi \frac{[L_{Q\text{con-se}} - L_{Q\text{off}}]}{[E_{Q\text{on}} - E_{Q\text{off}}]} \quad (1)$$

Here β_{std} is the luminance factor of the white standard as used in this illumination geometry (remember, these white standards are not Lambertian).

REPORTING: Same as main section in addition to reporting the specular port diameter and angular subtense, and the detector measurement field on the display.

COMMENTS: An assessment of the display's reflection properties would be valuable in determining if this specular excluded measurement would be appropriate. If an observer holding the display can see a distinct virtual image off the display surface in the specular direction, then this measurement should work well. However, if the virtual image is completely fuzzy, then this measurement will not be robust, and should be avoided or used with great care.

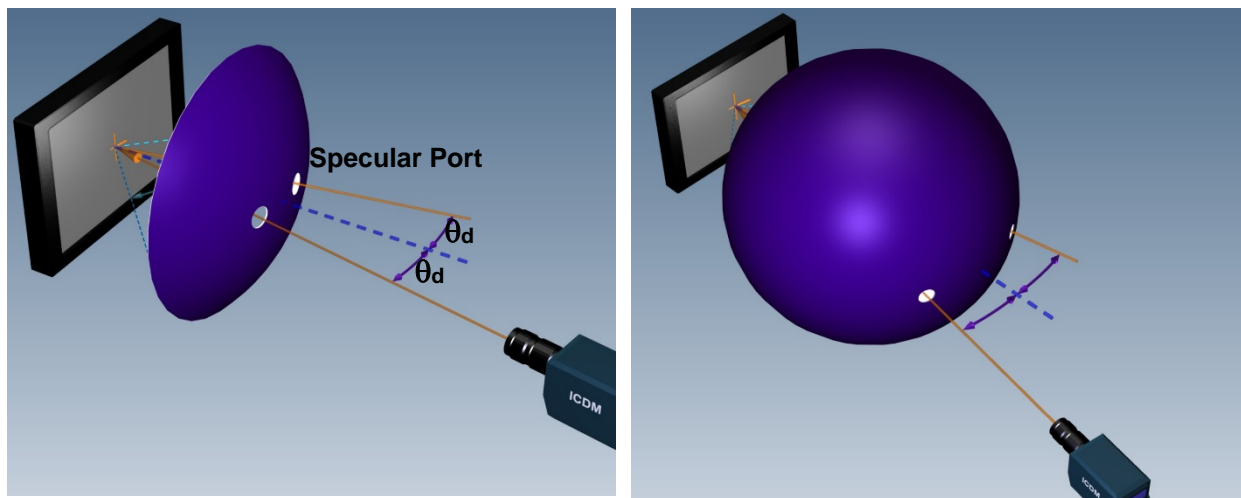


Fig. 1. Spherical cap illumination configuration with specular excluded (left). Displaced integrating sphere implementation is on the right.



11.5. Ring-light reflection

DESCRIPTION

We measure the reflectance factor of a display with a selected color screen under ring-light illumination. The luminous ring-light reflectance factor can be calculated from the spectral measurement or determined directly by a photometric measurement. Units: none; and Symbol: $R_{45/0}$.

SETUP

As defined by these icons, standard setup details apply (§ 3.2).



Ring-light illumination should provide uniform directed illumination on the display over all azimuthal angles at a given inclination angle θ_r . It should also provide a uniform illumination over the measurement field of the LMD. The ring-light emitting surface should be parallel to the display surface and symmetric about the display's center of screen. The distance between the ring-light and display surface should be adjusted to obtain an inclination angle $\theta_r > 30^\circ$, with a ring subtense of $< 5^\circ$. It is recommended to use an inclination angle of $\theta_r = 45^\circ$. The detector is aligned to view the center of the display and normal to the surface. The detector is focused on the display surface. The optical axis of the detector should be centered within the ring-light's clear aperture. The use of small ring-lights should be avoided—see Fig. 1. It is suggested that the distance of the ring-light from the display should be much greater than the thickness of the display's optical layers—see Fig. 2.

Illuminance Measurement

It is recommended that the illuminance E_{ring} be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known reflectance factor $R_{\text{std-ring}}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps

Quartz-tungsten-halogen lamps stabilized to less than $\pm 1\%$ per hour from a fiber-optic illuminator are often used as lamps. Most fiber-optic illuminators employ IR absorbing filters that reduce the red output providing a slightly greenish illumination. If reflection measurements are performed on emissive displays, the ring-light illuminance needs to be sufficiently high such that the reflected light luminance is significantly larger than the display luminance. White LEDs and xenon sources are finding applications for such fiber-optic illuminators.

PROCEDURE

1. Measure the luminance L_Q at the center of the display color pattern with the ring light OFF (this can be accomplished by disconnecting the fiber optic cable from the lamp source or shuttering the lamp).
2. Measure the luminance $L_{Q,45/0}$ of the display with the ring light ON and the display in its desired color state.
3. Replace the display with the white standard or illuminance meter in the same measurement position. Measure the luminance L_{std} of the standard from the ring-light illumination or the illuminance $E_{\text{f,dir}}$ with an illuminance meter.

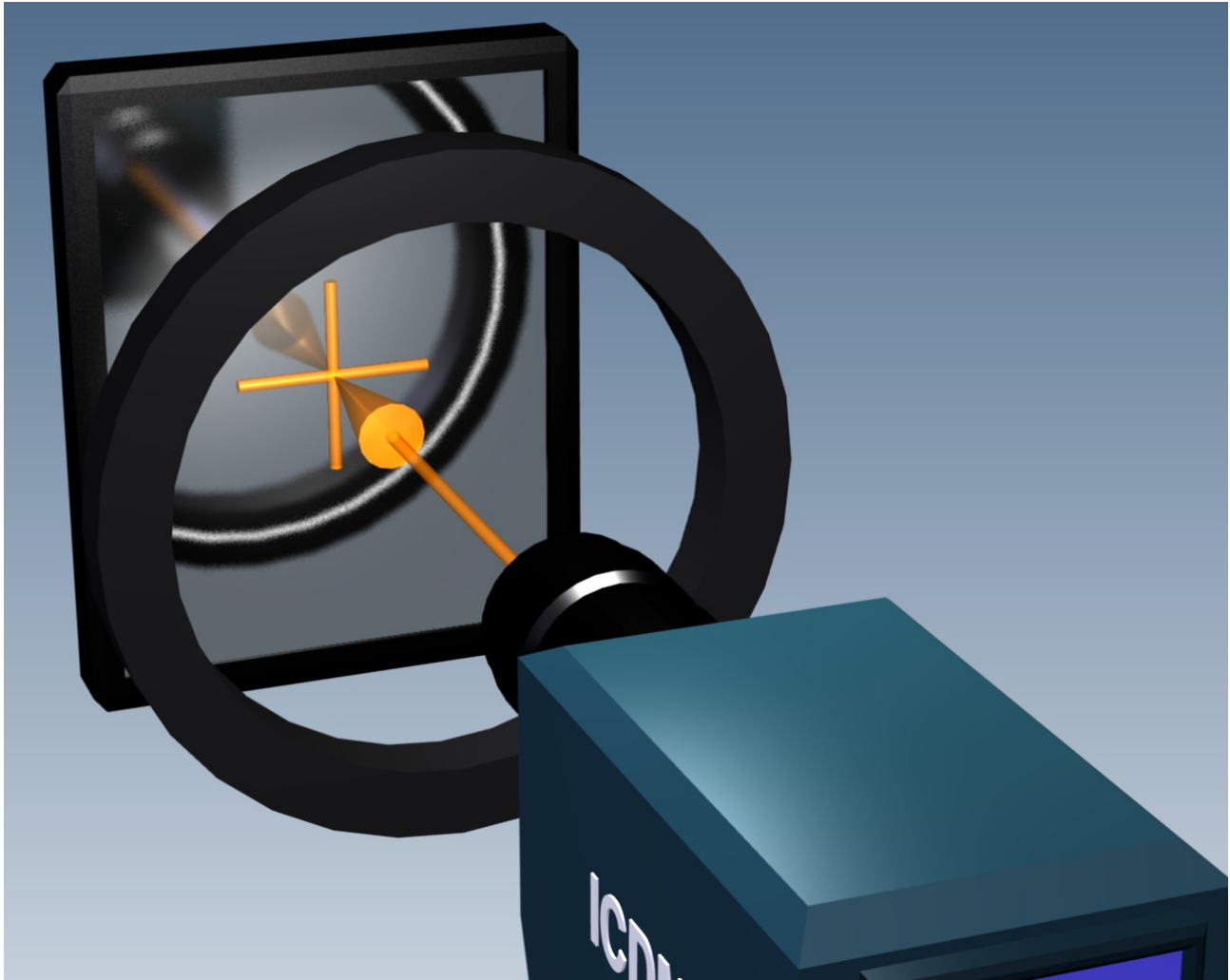


FIGURE 11.1. Ring-light illumination configuration.

ANALYSIS

The ring-light luminous reflectance factor $R_{45/0}$ is determined as follows

$$R_{Q,45/0} = R_{\text{std-ring}} \frac{L_{Q,45/0} - L_Q}{L_{\text{std}}} = \frac{\pi(L_{Q,45/0} - L_Q)}{E_{\text{f,dir}}} \quad (11.1)$$

For reflective displays L_Q will be zero.

REPORTING

Report the calculated luminous reflectance factor $R_{Q,45/0}$ of the display at the applied color Q , and the correlated colour temperature T_c of the ring-light illumination used in the measurement, the luminance values $L_{Q,45/0}$ and L_Q , and the calculated illuminance $E_{\text{b,dir}}$ on the display.



TABLE 11.1. Analysis example.

Sample data only: Do not use any values shown to represent expected results of your measurements.

Display luminance L_Q (cd m^{-2})	250
Display luminance with ring light ON $L_{Q,45/0}$ (cd m^{-2})	330
White standard luminance L_{std} (cd m^{-2})	9263
Known $R_{\text{std-ring}}$	0.97
Calculated luminous reflectance factor $R_{Q,45/0}$.00838

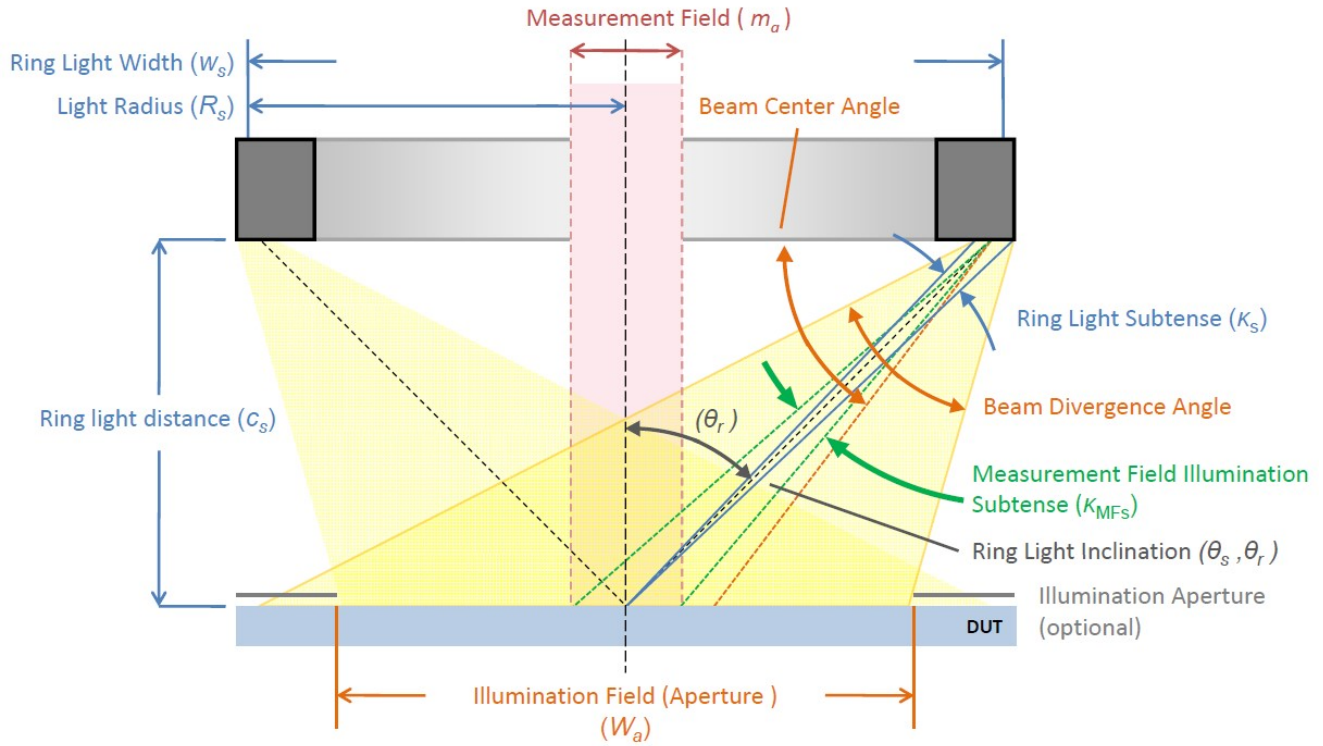


FIGURE 11.2. Details of ring-light configuration, side view.

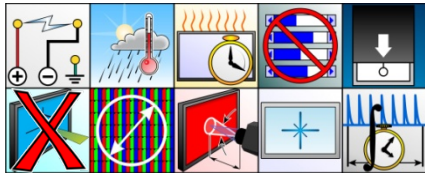


11.6 SMALL-SOURCE REFLECTION

CAUTION: The results of this measurement can be strongly affected by the presence of a haze component or matrix scatter component. Particularly for smaller angles ($<20^\circ$) and if a virtual distinct image of the source is not available (reflection is primarily haze or diffuse reflection) the results can be very sensitive to alignment errors, geometry, and the size of the measurement field of the detector.

DESCRIPTION: We measure the luminance factor or reflectance factor of a display with a selected color screen under illumination from a small directed light source. **Units:** none; and **Symbol:** $\beta_{\theta_s/\theta_d}$, R_{θ_s/θ_d} .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: A directed light source (collimated or discrete) shall provide directed illumination on the display surface at a given source inclination θ_s and azimuth angle ϕ_s . It is recommended that the detector angle from the specular direction be $\geq 30^\circ$ for robust measurements whenever the display exhibits a strong haze component.

The detector is aligned to view the center of the display at an inclination θ_d and azimuth angle ϕ_d . The detector is focused on the display surface. **Collimated Source:** One advantage of using a collimated source is that it exhibits a uniform cross-section whereas a discrete source away from the normal of the display will exhibit an inverse-square nonuniformity across the measurement field on the display surface. Collimated sources well simulate the sun's illumination nature of having a parallel beam of light. **Discrete Source:** If a discrete source is used, it should have a subtense of $\psi \leq 5^\circ$. The subtense of the source should be progressively reduced as the measurement geometry approaches the specular direction. To simulate sources like the sun or moon, it is recommended that a subtense of $\psi = 0.5^\circ$ be used at a distance of $c_s \geq 1$ m. The source should be uniform across its exit port to 1 %. The discrete light source may be implemented by using sources like an integrating sphere with a small exit port or an optical fiber bundle (be very careful of nonuniformities of the illumination distribution, aiming is important). In most cases, the detector should be aligned normal to the display surface, with an angular aperture of $\leq 5^\circ$ and measurement field angle of $\leq 2^\circ$.

Illuminance Measurement: It is recommended that the illuminance E_{direct} be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known luminance factor $\beta_{\text{std-direct}}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: If reflection measurements are performed on emissive displays, the illuminance needs to be sufficiently high such that the reflected light luminance is significantly larger than the display luminance. Lamps used in collimated sources should be stabilized to less than ± 1 % per hour drift. If quartz-tungsten-halogen lamps are used in collimated sources care must be exercised that the IR is reduced (usually by KG-3 filters) so they don't heat the display surface. LEDs are finding application for both collimated and discrete sources.

PROCEDURE:

1. Measure the luminance L_Q at the center of the display color pattern with all sources OFF or shuttered off.
2. Measure the luminance $L_{Q\text{direct}}$ of the display with the directed light source ON.
3. Replace the display with the white standard or illuminance meter in the same measurement position. Measure the luminance $L_{\text{std-direct}}$ of the standard from the directed illumination or illuminance E_{direct} with an illuminance meter.

ANALYSIS: The luminous reflectance factor $\beta_{Q\theta_s/\theta_d}$ is determined in the following:

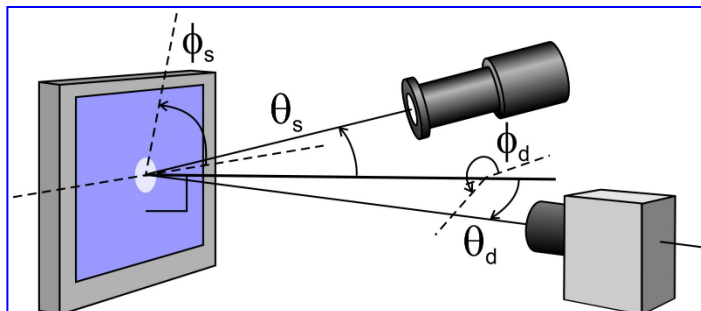


Fig. 1. General geometry for a small-source illumination configuration with collimated illumination shown.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example	
Display luminance L_Q (cd/m ²)	250
Display luminance with directed light ON $L_{Q\text{direct}}$ (cd/m ²)	330
White standard luminance $L_{\text{std-direct}}$ (cd/m ²)	9263
Known $\beta_{\text{std-direct}}$	0.97
Calculate $\beta_{Q\theta_s/\theta_d}$.00838



$$\beta_{Q\theta_s/\theta_d} = \beta_{\text{std-direct}} \frac{L_{Q\text{direct}} - L_Q}{L_{\text{std-direct}}} = \frac{\pi(L_{Q\text{direct}} - L_Q)}{E_{\text{direct}}} \quad (1)$$

For reflective displays, L_Q will be zero.

REPORTING: Report the calculated luminance factor $\beta_{Q\theta_s/\theta_d}$ of the display at the applied color and the CCT of the illumination used in the measurement. This measurement can be very sensitive to the measurement geometry. Therefore, the illumination and detection geometry must be clearly defined. The report should include θ_s , ϕ_s , c_s , source subtense, source type, θ_d , ϕ_d , c_d , measurement field angle, angular aperture, and detector type.

COMMENTS: None.

11.6.1 DIRECTED-SOURCE MAXIMAL CONTRAST

CAUTION: This measurement must be made with great care. It is designed to simulate how a hand-held reflective or transmissive display might be manipulated under direct sunlight to obtain the best readability. The reproducibility of this measurement can suffer because of the reflection properties of the display and the source-detector geometry. However, because a reflection parameter is not being measured and only a contrast it can be successful.

DESCRIPTION: We measure the maximum contrast of a reflective or transmissive mobile display under illumination from a collimated source.

Units: none **Symbol:** C_{DSMRC} .

APPLICATION: This measurement method is particularly useful for reflective and transmissive mobile displays where the orientation of the display may be readily adjusted by the user relative to the sun and the viewing direction.

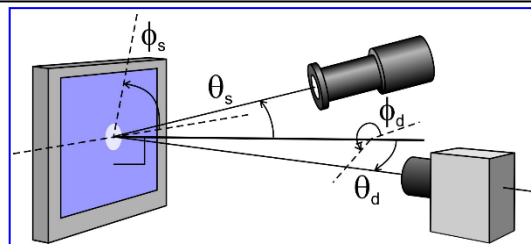


Fig. 1. Directed-source maximal contrast configuration.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use a collimated source to simulate sunlight illumination. If a collimated source is not available a small source with subtense $\psi \leq 5^\circ$ placed at a distance $c_s > 1$ m may work sufficiently well. The source and detector may be moved about the center of the display to obtain the maximum contrast for a readable display. The specular configuration of source and detector must be avoided if the display has a specular component of reflection, and a collimated source is employed.

PROCEDURE: Often the easiest implementation of this measurement is obtained by moving the source and display or detector using motorized rotational positioners.

1. Obtain approximate angles of source and detector by looking with your eye at the display of text to obtain the best contrast and readability as you move the source about the center of the display. Alternatively, you can estimate these angles by taking the display outside in sunlight or beneath a bright light. Once these angles are determined, configure the apparatus to approximate these angles.
2. Move the source and detector about the center of the screen while determining the contrasts by measuring the white screen luminance L_{Wi} and black screen luminance L_{Ki} at each orientation and calculate the contrast $C_i = L_{Wi}/L_{Ki}$.
3. Determine the angles that produce the maximum contrast of the set of measured contrasts C_i , $C_{\text{DSMRC}} = \max(C_i)$.

ANALYSIS: None, other than calculating the contrasts and determining the maximum contrast.

REPORTING: Report the directed-source maximal contrast and the source and detector angles to no more than three significant figures. The measurement result must be reported as the directed-source maximal contrast to avoid any confusion with other contrast metrics.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

$\theta_s =$	12	°
$\phi_s =$	45	°
$\theta_d =$	0	°
$\phi_d =$	0	°
C_{DSMRC}	3.42	



COMMENTS: Note that the contrast must be usable, that is, it must create text that is readily readable. There are cases where the contrast is great but the luminance of white is not great enough to produce readable text. Often the display is observed from the normal direction.

REFLECTION

REFLECTION



11.6.2 SMALL-SOURCE SPECULAR REFLECTION

CAUTION: This measurement should be avoided unless extraordinary care is taken. The results can be strongly affected by the presence of a haze component or matrix scatter component. Particularly if a virtual distinct image of the source is not available (reflection is primarily haze or diffuse reflection) the results are very sensitive to alignment errors, geometry, and the measurement field of the detector, and this method should not be used.

DESCRIPTION: Measure the spectral reflectance of a display in the specular direction, using a selected color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) screen, with a small, directed light source. This method should be avoided if the display appears to have a significant haze component. **Units:** none; and **Symbol:** ζ_{SSS} , R_{SSS} , $\zeta(\lambda)_{SSS}$, $R(\lambda)_{SSS}$.

SETUP: Similar to the main section with $\theta_d = \theta_s$ and $\phi_d = \phi_s + 180^\circ$. Additionally, it is important that the measurement field of the detector be contained within the distinct image of the source and that the detector is focused on that distinct image. If there is no distinct image, then this measurement is *not* recommended.

PROCEDURE: To measure the luminance of the source we need to unfold the source-detector geometry so that the detector is looking directly at the source at the same distance used in the folded geometry (preserve $c_s + c_d$).

1. Measure the luminance L_Q at the center of the display color pattern with the source OFF or shuttered.
2. Measure the luminance L_{QSSS} with the source on.
3. Unfold the source-detector geometry with the display removed and measure the luminance of the source L_s .
Alternatively, place a calibrated mirror or black glass with specular reflectance ζ_m on the display surface and measure the reflected luminance L_m of the source thereby adjusting it to give the luminance of the source $L_s = L_m / \zeta_m$. Focus the detector on the source.

ANALYSIS: The specular reflectance is given by: $\zeta_{SSS} = (L_{QSSS} - L_Q) / L_s$. L_Q is zero for reflective displays.

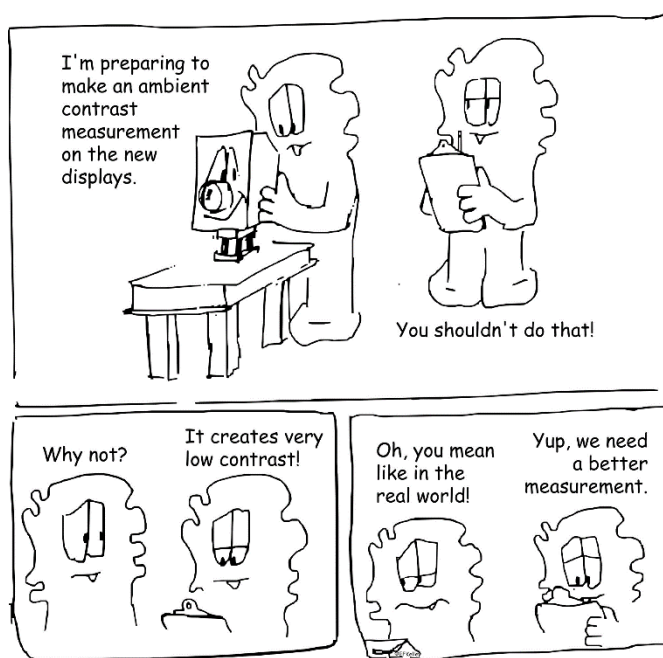
REPORT ING: Report ζ_{SSS} , the source size and distance c_s , the detector distance c_d , and the specular angle θ_d .

COMMENTS:

(1) ISO 9241-305, subclause 6.5.1 recommends using a discrete uniform source, implemented by using an integrating sphere with a small exit port having a subtense of 1° at a distance of 500 mm from display. The 1° small source specular reflection measurement can be used in concert with the 15° extended source measurement (Chapter 11.7.3) to determine the type of display reflectance in the regular (specular) configuration. If the display is mainly specular then the results of the measurements at 1° and 15° will be close; if it is mainly diffuse (strong haze) then the result at 1° will be substantially smaller than that at 15° .¹

(2) Sensitivity: In addition to the specular reflection component (if present), this measurement method will include the small amount of diffuse haze included within the source subtense $\Psi_s = 1^\circ$.

¹ Becker, M.E. (2002), Measurement of Display Scattering, Proc. 22nd IDRC, 803-805.



CARTOON RECYCLING

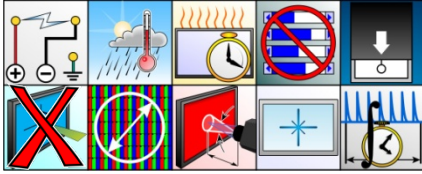


11.7 LARGE-SOURCE REFLECTION

DESCRIPTION: We measure the luminance factor or reflectance factor of a display with a selected color Q screen under illumination from a large discrete (or directed) uniform light source as described in Chapter 11.1.3.2. The specular reflectance is handled separately under another measurement

method. **Units:** none; and **Symbol:** $\beta_{Q\theta_s/\theta_d}$, R_{θ_s/θ_d} .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: A large discrete or directed uniform light source at a distance c_s from the center of the screen provides directed illumination on the center of the display surface at a given source inclination θ_s and axial angle ϕ_s . The detector is placed

a distance c_d from the center of the screen at an inclination angle of θ_d and axial angle ϕ_d . The detector is focused on the display. The directed light source should generally have a subtense of between 5° and 30° and be placed at least 0.5 m from the display center. Whenever a nontrivial haze or matrix scatter is present, it is recommended that the detector angle from the specular direction be $\geq 30^\circ$ for robust measurements, and the source should be uniform across its exit port to within 1 %. The directed light source may be implemented by using sources like an integrating sphere with a well-defined exit port.

Illuminance Measurement: It is recommended that the illuminance $E_{Q\text{direct}}$ be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known luminance factor $\beta_{\text{std-direct}}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: Quartz-tungsten-halogen lamps stabilized to less than $\pm 1\%$ may be used. If reflection measurements are performed on emissive displays, the lamp illuminance needs to be sufficiently high such that the reflected luminance is much larger than the display darkroom luminance. White LEDs are finding application for such sources.

PROCEDURE: We assume the display luminance does not affect the source.

1. Measure the luminance L_Q at the center of the display color pattern with the source OFF (either shuttered or turned off).
2. Measure the luminance $L_{Q\text{direct}}$ of the center of the display with the directed light source ON.
3. Measure the illuminance $E_{Q\text{direct}}$ from the source either directly with a cosine-corrected illuminance meter or by using a white standard (or calibrated target) in the same measurement position and measure the luminance $L_{\text{std-direct}}$ from the directed source illumination.

ANALYSIS: The luminance factor $\beta_{Q\theta_s/\theta_d}$ is determined by

$$\beta_{Q\theta_s/\theta_d} = \beta_{\text{std-direct}} \frac{(L_{Q\text{direct}} - L_Q)}{L_{\text{std-direct}}} = \frac{\pi(L_{Q\text{direct}} - L_Q)}{E_{\text{direct}}} \quad (1)$$

For reflective displays, L_Q will be zero.

REPORTING: Report the calculated luminance factor $\beta_{Q\theta_s/\theta_d}$ of the display at the applied color Q , the corresponding CCT of the calculated light source, and the CCT of the illumination used in the measurement. This measurement can be very sensitive to the measurement geometry. Therefore, the illumination and detection geometry must be clearly defined: The report should include the source angles (θ_s , ϕ_s) the source distance c_s , source subtense ψ_s , source type, θ_d , the detector distance c_d , and detector angles (θ_d , ϕ_d). If the reflectance factor $\beta_{Q\theta_s/\theta_d}$ is recorded, the report must include the measurement field angle, angular aperture, and detector type.

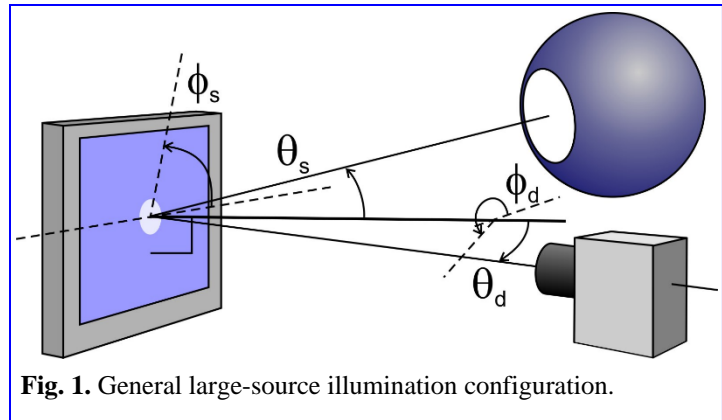


Fig. 1. General large-source illumination configuration.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example	
Display luminance L_Q (cd/m ²)	250
Display luminance with directed light ON $L_{Q\text{direct}}$ (cd/m ²)	330
White standard luminance $L_{\text{std-direct}}$ (cd/m ²)	9263
Known $\beta_{\text{std-direct}}$	0.97
Calculate $\beta_{Q\theta_s/\theta_d}$.00838



11.7.1 LARGE-SIDE-SOURCE REFLECTION

CAUTION: This measurement can be strongly affected by alignment errors if the display has a significant haze component. Care should also be taken to avoid stray light and ambient background errors. This is not a recommended measurement method unless extreme care is taken especially if there is significant haze.

DESCRIPTION: Measure the luminance factor of a display exhibiting a screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) with a single large, directed source in the horizontal plane. **Units:** none; and **Symbol:** β_{QLSS} , R_{QLSS} , $\beta(\lambda)_{QLSS}$, $R(\lambda)_{QLSS}$.

This method is not recommended for robust measurement results especially whenever haze is nontrivial. The illuminance from the source is not uniform over the measurement field and haze can make the measurement results very sensitive to alignment.

SETUP: Use the setup conditions of the main general method with the detector at the normal of the display ($\theta_d = 0$, $\phi_d = 0$) and the source at an inclination angle of $\theta_s \geq \pm 30^\circ$ with source subtense of $\psi_s \geq 15^\circ$.

PROCEDURE: Same as the main section.

ANALYSIS: Same as the main section.

REPORTING: Same as the main section.

COMMENTS: This measurement is intended to be compatible with ISO 9241-305 when $\psi_s = 15^\circ$.

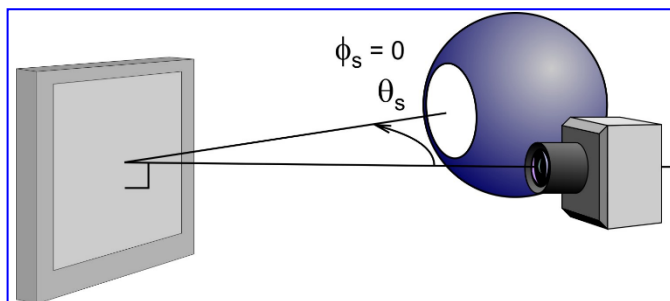


Fig. 1. Large source to the side of the detector.

11.7.2 DUAL-LARGE-SOURCE REFLECTION

CAUTION: This measurement can be strongly affected by alignment errors if the display has a significant haze component. Care should also be taken to avoid stray light and ambient background errors.

DESCRIPTION: Measure the luminance factor of a display using a screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) with a two large, directed light sources placed at $\pm 30^\circ$ in the horizontal plane with the detector at the normal. The sources are placed at a distance of $c_s = 500$ mm or more and each source subtense must be $\psi_s = 15^\circ$. The suggested detector distance is $c_d = 500$ mm or more. **Units:** none; and **Symbol:** β_{QDLS} , R_{QDLS} , $\beta(\lambda)_{QDLS}$, $R(\lambda)_{QDLS}$.

SETUP: This is a doubling of the sources used in the main section and the above method. It produces a more uniform illuminance distribution across the measurement field at the center of the screen than the above method. Here the detector is at the normal ($\theta_d = 0$, $\phi_d = 0$) and the sources are at ($\theta_s = \pm 30^\circ$, $\phi_d = 0$). Both the sources and detector are at 500 mm from the screen center or more ($c_s \geq 500$ mm, $c_d \geq 500$ mm), and the sources must subtend $\psi_s \geq 15^\circ$.

PROCEDURE: Same as the main section.

ANALYSIS: Same as the main section.

REPORTING: Same as the main section, but with specifications for both sources included.

COMMENTS: This measurement is intended to be compatible with ISO 9241-305 when $\psi_s = 15^\circ$.

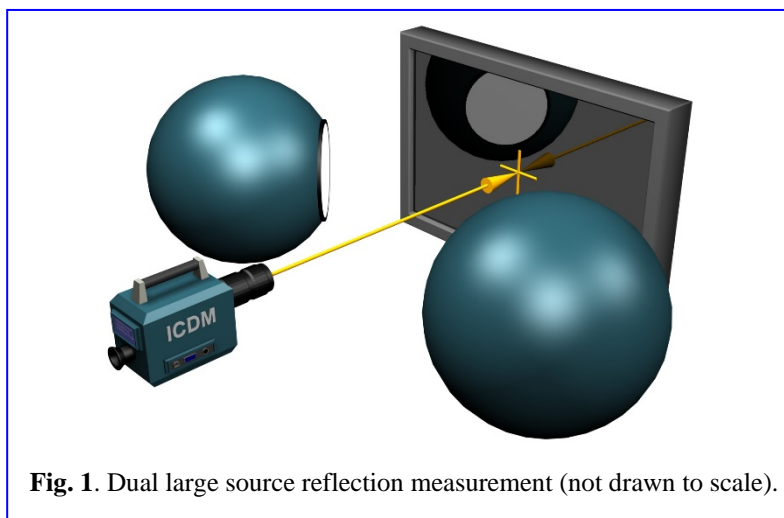


Fig. 1. Dual large source reflection measurement (not drawn to scale).



11.7.3 LARGE-SOURCE SPECULAR REFLECTION

CAUTION: The uncertainty of this measurement can be increased significantly by the reflection properties of the display, particularly if there is a nontrivial haze component of reflection, strong Lambertian component, or very strong matrix scatter. This measurement is best performed on displays that have a nontrivial specular component of reflection; that is, displays that exhibit a distinct virtual image of the source.

DESCRIPTION: Measure the specular reflectance of a display with a screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under illumination of a large, directed light source.

Units: none; and **Symbol:** ζ_{QLSS} .

SETUP: Same as main but with the source and detector in a specular configuration at $\pm 15^\circ$:

source at: $\theta_s = +15^\circ$, $\phi_d = 0$, detector at $\theta_d = -15^\circ$, $\phi_d = 0$, source distance $c_s \geq 500$ mm, detector distance $c_d \geq 500$ mm, and source subtense $\psi_s = 15^\circ$. It is recommended to use a discrete source (integrating sphere) with a nonuniformity of less than 1%.

PROCEDURE: We will assume that the illuminance from the source is not affected by the display being on or off. The detector should be focused on the virtual image of the source.

1. Measure the luminance L_Q at the center of the display color pattern with the source OFF (either shuttered or turned off).
2. Measure the luminance L_{QLSS} of the center of the display with the directed light source ON.
3. Measure the luminance L_s of the center of the source either by unfolding the system and removing the display so that the detector to source distance is the same as the folded geometry or by placing a calibrated mirror or black glass with specular reflectance ζ_m on the display surface and measure the reflected luminance L_m of the source thereby adjusting it to give the luminance of the source $L_s = L_m / \zeta_m$. Focus the detector on the source.

ANALYSIS: The specular reflectance is given by:

$$\zeta_{QLSS} = (L_{QLSS} - L_Q) / L_s. \quad (1)$$

The luminance L_Q is zero for reflective displays.

REPORTING: Report the geometry of the detector-source-display system with the specular reflectance ζ_{QLSS} .

COMMENTS: (1) **Sensitivity:** In addition to the specular reflection component (if present), the reflected light within the source subtense $\psi_s = 15^\circ$ can include the Lambertian, diffuse haze, and matrix scatter components. The difference between this large-source measurement and the small-source measurements in Chapter 11.6.2 is primarily the extent of the contribution of haze¹. If the display has a nontrivial haze component, then this measurement can become very sensitive to the configuration of the apparatus and characteristics of the detector. In this case the variable aperture source method of 11.8 is better suited for characterizing complex reflection behavior.

11.7.3.1 Removal of Lambertian Component from Specular Result

CAUTION: If the measurement of specular reflectance measured in 11.7.3 included a non-trivial haze component, then the removal of a Lambertian component will still not remove the haze contribution. Therefore, in the presence of non-trivial haze, this method may not provide a good estimate of the true specular reflectance.

DESCRIPTION: We calculate an estimate of the true specular reflectance from the previous specular measurement when we can subtract off a Lambertian component from the specular component for a display with a display screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.). **Units:** none; and **Symbol:** ζ_Q .

APPLICATION: This method is *only* applicable to displays that do not have a significant haze component of reflection or significant matrix scatter.

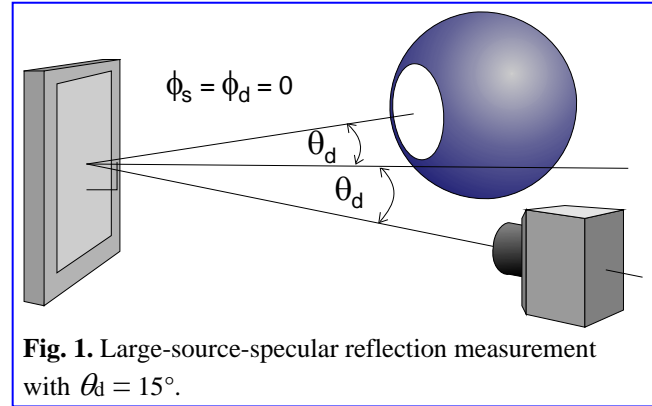


Fig. 1. Large-source-specular reflection measurement with $\theta_d = 15^\circ$.

¹ E. F. Kelley, G. R. Jones, and T. A. Germer, "Display Reflectance Model Based on the BRDF." Displays, Vol. 19, No. 1, June 30, 1998, pp. 27-34 (June 1998).



11.7.3.2. Annulus Source Specular Reflection

CAUTION: If the measurement surface is dominated by Lambertian or haze light scattering, with a small specular component, then the specular reflectance may not be measurable. In that case, a small subtense annulus source ($\leq 1^\circ$) will have the best chance in measuring the specular reflectance. The measurement is limited by the stray light and sensitivity of the LMD.

DESCRIPTION

Measure the specular reflectance of a display with a screen color Q ($Q = W, R, G, B, C, M, Y, K, S, \dots$) under illumination of a small to large, directed annulus light source. Recommended when a strong Lambertian or a nontrivial haze component is present. Once the specular reflectance is determined, this method can also be used to determine the haze reflectance factor. Units: none; and symbol: $\zeta_{Q,ALSS}$.

APPLICATION

This method mainly applies to reflective, emissive, transmissive (LCDs), and transparent direct view displays that are flat or have a relatively large radius of curvature.

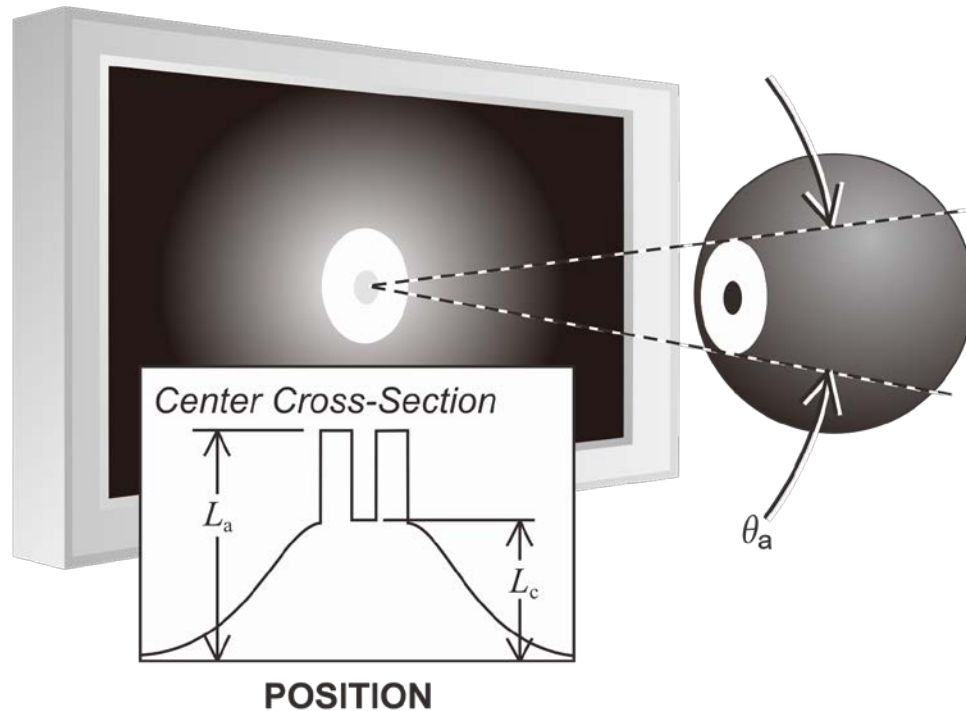


FIGURE 11.29. Schematic of an annulus light source viewed in the specular direction. Inset illustrates an example of reflected luminance cross-section through the center.

SETUP

Same as main but with the source and detector in a specular configuration at $\pm 15^\circ$ (typically): source at: $\theta_s = +15^\circ$, $\phi_s = 0$, detector at $\theta_d = -15^\circ$, $\phi_d = 0$, source distance $c_s \geq 500$ mm, detector distance $c_d \geq 500$ mm, and source subtense $1^\circ \leq \psi_s \leq 15^\circ$, where the surface of the display lies at the center of the spherical coordinate system. It is recommended to use a discrete source, *e.g.*, integrating sphere with a nonuniformity of less than 1%. An opaque circular stop with a subtense $\leq 0.3^\circ$ (from the display) is centered within the near-Lambertian light source (see Fig. 11.29). In practice, this opaque stop can be held in place at the front of the source by narrow vertical tether lines. The measurement field of the LMD should be small enough to lie completely within the opaque stop (for example 0.1°) and



measure its luminance (L_c or L_g), or adjacent to the stop in the uniform annulus region (L_m or L_a). The luminance measurement adjacent to the opaque stop should be within 1° of the center of the stop. Ideally the luminance of the source should be larger than 5000 cd m^{-2} and the LMD should have a measurement range that extends below 0.001 cd m^{-2} with its small measurement field. A spectroradiometer may be used as the LMD to measure the spectral specular reflectance. Further background information about this method is described in Appendix B17.2.

PROCEDURE

We will assume that the illuminance from the source is not affected by the display being on or off. The detector should be focused on the virtual image of the source.

1. Position the annulus light source normal to the LMD at a distance $c_s + c_d$ away. This is the unfolded measurement configuration. Alternatively, a calibrated specular reflectance standard like black glass can be used in the folded configuration to determine the source luminance. Only the direct unfolded configuration method will be described below.
2. Directly measure the luminance L_g within the opaque center of the annulus source.
3. Rotate the LMD (or annulus source) slightly about the center of the spherical coordinate system so that the LMD measurement field lies just left of the opaque center of the annulus source.
4. Measure the left-side luminance L_{ml} of the annulus source.
5. Rotate the LMD (or annulus source) slightly about the center of the spherical coordinate system so that the LMD measurement field lies just right of the opaque center of the annulus source.
6. Measure the right-side luminance L_{mr} of the annulus source.
7. Place the display surface area to be measured at the center of the spherical coordinate system and align the LMD and annulus source in the 15/15 illumination/detection specular configuration.
8. Turn on the display to the desired color state Q with a full screen pattern and allow the luminance to stabilize.
9. Align the LMD measurement field within the reflected virtual image of the opaque center of the annulus source. Measure the reflected luminance $L_{c,ON}$ from the annulus source with the display ON.
10. Block the light from the annulus source and measure the luminance $L_{c,OFF}$ from the direct display emission. For reflective displays, $L_{c,OFF} = 0$ and this step can be skipped.
11. Unblock the light from the annulus source. Rotate the LMD (or annulus source) slightly about the center of the spherical coordinate system so that the LMD measurement field lies just left of the virtual image of the opaque center of the annulus source. Measure the reflected luminance $L_{al,ON}$ from the annulus source with the display ON.
12. Block the light from the annulus source and measure the luminance $L_{al,OFF}$ from the direct display emission. For reflective displays $L_{al,OFF} = 0$ and this step can be skipped.
13. Unblock the light from the annulus source. Rotate the LMD (or annulus source) slightly about the center of the spherical coordinate system so that the LMD measurement field lies just right of the virtual image of the opaque center of the annulus source. Measure the reflected luminance $L_{ar,ON}$ from the annulus source with the display ON.
14. Block the light from the annulus source and measure the luminance $L_{ar,OFF}$ from the direct display emission. For reflective displays $L_{ar,OFF} = 0$ and this step can be skipped.
15. Replace the display with a white reflectance standard normal to the LMD and at the same distance as the surface of the display. Then rotate the reflectance standard to the 15/15 illumination/detection geometry and measure the reflected luminance $L_{std,15/15}$ from the reflectance standard. The white standard should be calibrated ($\rho_{std,15/15}$) for this 15/15 illumination/detection geometry, or the substitution method can be used to determine the illuminance $E_{15/15}$ at the 15/15 illumination/detection geometry from the 45/0 configuration below. Alternatively, an illuminance meter can replace the reflectance standard to measure the illuminance at the measurement plane.

Use the following extended procedure to measure the reflectance factor of the haze component in the specular direction.



16. Measure the Lambertian diffuse reflectance of the display following 11.7.1 (without opaque center) but using a $\psi_s = 15^\circ$ subtense source, with $\theta_s = +45^\circ$, $\varphi_s = 0^\circ$, detector at $\theta_d = 0^\circ$, $\varphi_d = 0^\circ$, source distance c_s and detector distance c_d unchanged from above.
17. Place a white reflectance standard normal to the LMD and at the same distance as the surface of the display. The white standard should be calibrated ($\rho_{\text{std},45/0}$) for this 45/0 illumination/detection geometry. Alternatively, an illuminance meter can replace the reflectance standard to measure the illuminance at the measurement plane.
18. With the LMD focus maintained at the same source distance as above, measure the reflected luminance $L_{\text{std},45/0}$ from the white standard.
19. Replace the white standard with the display normal to the LMD and at the same distance c_d as above.
20. Turn on the display to the same full screen color state Q as above and allow the luminance to stabilize.
21. With the LMD focus maintained at the same source distance as above, measure the reflected luminance $L_{\text{lamb},\text{ON}}$ from the same display measurement area as above with full screen color Q with the source ON.
22. Block the light from the light source and measure the luminance $L_{\text{lamb},\text{OFF}}$ from the direct display emission. For reflective displays $L_{\text{lamb},\text{OFF}} = 0$ and this step can be skipped.



ANALYSIS

The specular reflectance in the specular viewing direction for the annulus light source is given by

$$\zeta_{Q,ALSS} = \frac{L_a - L_c}{L_s} = \frac{L_a - L_c}{L_m - L_g} \quad (11.1)$$

where

$$L_m = \frac{L_{ml} + L_{mr}}{2} \quad (11.2)$$

and

$$L_s = L_m - L_g \quad (11.3)$$

is the annulus source luminance. Eqs. 11.4 and 11.5 describe the average total reflected luminance and diffuse reflected luminance, respectively.

$$L_a = \frac{(L_{al,ON} - L_{al,OFF}) + (L_{ar,ON} - L_{al,OFF})}{2} \quad (11.4)$$

$$L_c = L_{c,ON} - L_{c,OFF} \quad (11.5)$$

To also obtain the reflection coefficients for the Lambertian and haze components, the Lambertian diffuse reflectance is given by

$$\rho_Q = \frac{\pi(L_{lamb,ON} - L_{lamb,OFF})}{E_{45/0}} \quad (11.6)$$

Where $E_{45/0}$ is measured directly with an illuminance meter or calculated from the reflected luminance of the white reflectance standard in the measured 45/0 illumination/detection geometry,

$$E_{45/0} = \pi \frac{L_{std,45/0}}{\rho_{std,45/0}} \quad (11.7)$$

The haze reflectance factor for the measured subtense source at the defined 15/15 illumination/detection geometry is given by

$$R_{Q,haze} = \frac{\pi L_c(1 + G) - \pi G L_a}{E_{15/15}} - \rho_Q \quad (11.8)$$

where the glare factor is

$$G = \frac{L_g}{L_m - L_g} \quad (11.9)$$

and

$$E_{15/15} = \pi \frac{L_{std,15/15}}{\rho_{std,15/15}} \quad (11.10)$$

REPORTING

Report the specular reflectance $\zeta_{Q,ALSS}$, the illumination/detection geometry, the measured color state, the annulus source subtense, L_m , L_g , L_a , L_c , the illuminance $E_{15/15}$, and the approximate correlated color temperature T_c of the source. When measured, also report the Lambertian diffuse reflectance ρ_Q , the subtense of the source used to measure the Lambertian reflectance, the illuminance $E_{45/0}$, the haze reflectance factor $R_{Q,haze}$, and how the illuminance values ($E_{15/15}$ and $E_{45/0}$) were measured.



COMMENTS

1. **Annulus light source:** The light source used to create the annulus source should ideally be near-Lambertian, uniform, stable, and emit a broadband spectrally smooth spectrum. One way to implement this annulus source is to place a small black piece of metal or plastic in the center of an integrating sphere port. The center of the annulus source should be small ($\leq 0.3^\circ$ subtense from the display) and completely opaque. This opaque center can be held in place by thin vertical tether lines above and below this stop. For glossy samples, it is useful for the luminance of the annulus source to be greater than $5,000 \text{ cd m}^{-2}$.
2. **Annulus source positioning:** It is useful to place the annulus source on a goniometric arm to swing the source to the optical axis of the LMD for direct source measurements, or for the 15/15 and 45/0 measurements.
3. **Alignment:** Since small angles are used in these measurements, it is valuable to use an alignment laser to verify the measurement geometry. It is also helpful to place the display on a rotation stage for easy angular motion.
4. **LMD requirements:** This method requires a spot LMD with a measurement field angle of 0.1° or less. A high sensitivity LMD is needed to obtain reliable measurements below 0.001 cd m^{-2} , especially for glossy surfaces and black color states. The user should be aware when the LMD has reached its noise floor during a measurement.
5. **Radiometric Measurements:** For greatest accuracy and flexibility, it is recommended to make spectrally resolved measurements and calculate the spectral reflection parameters—see comments in the introduction to this chapter.
6. **Imaging LMD:** A photometric imaging LMD can potentially be used to perform the luminance measurements for this method, although many imaging LMDs tend to have too much stray light and not enough sensitivity. The imaging LMD should be validated against a high sensitivity spot photometer. An imaging LMD with high dynamic range image capture is recommended. The imaging LMD should also have enough spatial resolution (more than 100 camera pixels) to measure the luminance profile in the opaque center of the annulus source.
7. **Illuminance measurements:** The illuminance on the display surface in the 15/15 or 45/0 illumination/detection geometry can be measured with an illuminance meter or calibrated white reflectance standard. In either case the tip of the illuminance meter or the surface of the reflectance standard should replace the display, lying in the same measurement plane, and centered within the measurement area of the LMD. The illuminance meter should have a cosine response with incident angle. If the white reflectance standard is only calibrated at the 15/15 or 45/0 illumination/detection geometry, the substitution method can be used to determine the reflectance for the other geometry using a simple ratio of reflected luminance measurements from the standard for the same light source and LMD.
8. **Small specular reflectance:** When the display surface has a small specular reflection component relative to a large diffuse component, there will be a better chance in resolving the specular component by using an annulus source having a subtense $\leq 1^\circ$. As the luminance of L_c approaches L_a (see Figure 11.29), the ability to resolve the specular component will depend on the veiling glare and sensitivity of the LMD.



11.7.4 PROXIMAL-SOURCE REFLECTION

DESCRIPTION: Measure the luminance factor of a display with a display screen color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under illumination of a large, directed light source in proximity to the display. The source has sufficient diameter so that when placed at $\theta_s = 45^\circ$ and the detector at $\theta_d = 30^\circ$ the specular-configuration line at $\theta_c = \theta_d$ intersects the surface of the source. **Units:** none; and **Symbol:** β_{QPS} .

APPLICATION: This method is particularly useful for displays that are not readily accessible in a laboratory setting such as displays recessed in a automobile dashboard.

SETUP: Similar to the main section with the following conditions: source at: $\theta_s = +45^\circ$, $\phi_s = 0$, detector at $\theta_d = -30^\circ$, $\phi_d = 0$, detector distance $c_d \geq 500$ mm, source distance c_s is as close as possible, and source subtense is large enough so that the specular line from detector to source intersects well within the disk of the source.

Illuminance Measurement: Because the display can affect the illuminance from the source, we must measure the illuminance without changing the apparatus geometry. This may be accomplished using a specially calibrated thin white or gray target place at the center of the screen and on (or very near) the surface of the screen that has been calibrated for this specific geometry with luminance factor β_{trgPS} .

PROCEDURE: Because of the proximity of the source to the display we must assume that the display can affect the source.

1. Measure the luminance L_{Qoff} at the center of the display color pattern with the source OFF (either shuttered or turned off). At the same time measure the illuminance E_{Qoff} using a specially calibrated (β_{trgPS}) thin white target and its luminance $L_{trgQoff}$ at the center of the screen.
2. Measure the luminance L_{Qon} of the center of the display with the directed light source ON. At the same time measure the illuminance E_{Qon} via a thin white target with luminance L_{trgQon} .

ANALYSIS: The luminance factor for the proximal source is:

$$\beta_{QPS} = \beta_{trgPS} \frac{L_{Qon} - L_{Qoff}}{L_{trgQon} - L_{trgQoff}} = \pi \frac{L_{Qon} - L_{Qoff}}{E_{Qon} - E_{Qoff}}. \quad (1)$$

REPORTING: Report the details of the geometry and β_{QPS}

COMMENTS: This measurement method is a replication of the SAE J1757-1 Standard Metrology for Vehicular Displays, Optical Performance. **Contrast Calculations:** (1) **Reflective Displays:** For reflective (only) displays the contrast for any illumination level is $C_{reflective} = \beta_{WPS}/\beta_{KPS}$. (2) **Emissive Displays:** For emissive displays we need the darkroom luminances of white L_W and black L_K ; then the contrast for a source illuminance of E_s is: $C_{emissive} = (L_W + \beta_{WPS}E_s)/(L_K + \beta_{KPS}E_s)$.

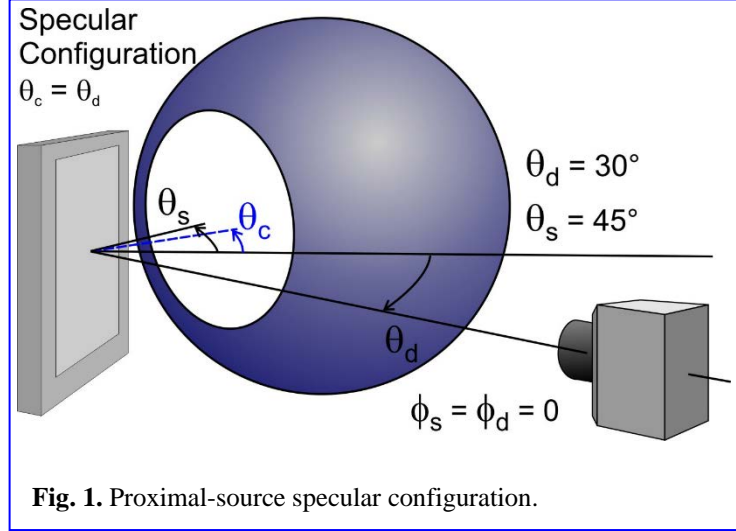


Fig. 1. Proximal-source specular configuration.

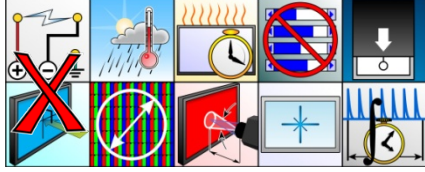


11.8 VARIABLE-APERTURE-SOURCE SPECULAR REFLECTION

DESCRIPTION: We measure the specular reflectance $\zeta = L/L_s$ as a function of source subtense or solid angle of a variable-aperture source (VAS) for relatively large source apertures. **Units:** None, and **Symbol:** ζ .

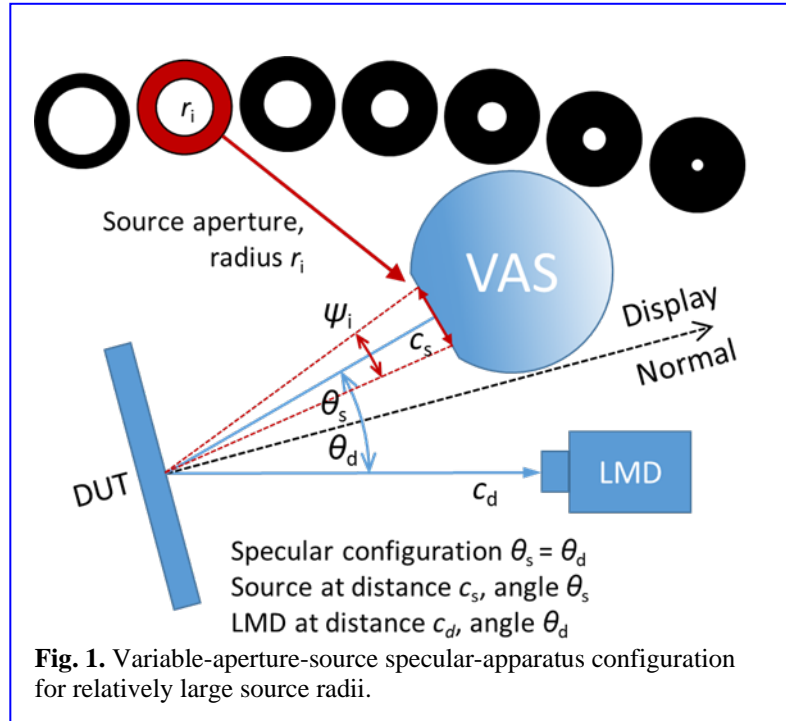
SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: The detector (LMD) is aligned in a horizontal plane with the center of the screen (DUT)



at an angle of inclination that is equal to the angle of light incidence (specular arrangement, $\theta_s = \theta_d = 15^\circ$, for example, other angles may be of interest as well). The source must be warmed up and stable, with a drift of no larger than 1 % per hour. The source must exhibit a nonuniformity no larger than 1 % as measured in nine places (the center, and at 75 % of the radius at locations top, top right, right, ... etc. around the port) for all apertures¹. The apertures should be sized with radii r_i to provide a range of source subtense ψ_i from 1° or less to 15° or more. Each of the apertures, $i = 1, 2, \dots, n$, follow the relationship between radius and subtense of:

$$\tan(\psi_i / 2) = r_i / c_s \quad (1).$$



The LMD should use a measurement field as small as is reasonably possible to ensure that the source illumination field is always overfilling the LMD's measurement field, even at the smallest aperture. The detector is to be focused on the aperture plane. A black glass plate placed at the same plane as the DUT can be used like a mirror to focus the LMD on the aperture before measuring the DUT. An LMD eyepiece camera is recommended to ensure that the LMD is aligned, overfilled and focused. The distance between source and DUT center is c_s ($c_s \geq 500$ mm suggested), and the distance between LMD and DUT center is c_d ($c_d \geq 500$ mm suggested). For apertures $< 1^\circ$ subtense, it may be necessary to move the LMD closer to the DUT and refocusing it to ensure an overfilled detector. As the apertures become smaller, the source luminance will generally increase. On the other hand, smaller apertures decrease the illuminance at the DUT. Therefore it is necessary to measure both the source luminance $L_{s,i}$ and the luminance $L_{Q,i}$ of the DUT set to the color Q for each aperture i . Then calculate the reflectance characteristic $\zeta_{Q,i}$ in the specular configuration as $\zeta_{Q,i} = L_{Q,i} / L_{s,i}$. For reflective displays that have a substantial color-dependent Lambertian reflection component, the measurement series has to be repeated for each display color Q ².

PROCEDURE: Repeat the following steps for each source aperture diameters $i = 1, 2, \dots, n$:

1. Align the light source and LMD in the specular configuration ($\theta_s = \theta_d$) relative to the measurement plane of the DUT.
2. Use a calibrated piece of black glass with specular reflectance $\zeta_{BG,s}$ for measuring the luminance $L_{BG,i}$ reflected from the VAS at each source subtense ψ_i . Alternatively, if the apparatus can be unfolded, the source luminance $L_{s,i}$ could be measured directly. But in practice, this can be cumbersome because of having to precisely realign the apparatus to the specular configuration after each change of aperture. Before starting the measuring series, focus on the virtual image of the smallest aperture.

¹ Such high uniformity can be achieved by a cylindrical extension of the integrating sphere source: Kelley, E.F., Dowd, A., Fong, A., Bronson, B. and Goodman, W. (2016), P - 64: Ultra - Uniform Oblong Integrating Light Source, SID Symposium Digest of Technical Papers, 47.

² An example of a practical implementation of this measurement is reported in Hertel, D. and Kelley, E. F. (2019), 78-1: Specular Reflection Measurements on Reflective E-paper Using a Variable Aperture Source. SID Symposium Digest of Technical Papers, 50: 1118-1121.



3. Replace the black glass with the DUT (in the same plane) set to the color Q , and measure the luminance $L_{Q,i}$ of the DUT at each source subtense Ψ_i .
4. Calculate the reflectance factor of the DUT in the specular configuration $\zeta_{Q,i}$ as the ratio of the measured luminance $L_{Q,i}$ of the screen relative to that of the calibrated black glass $L_{BG,i}$

$$\zeta_{Q,i} = \zeta_{BG,s} \cdot L_{Q,i} / L_{BG,i} \quad (2).$$

ANALYSIS: The measured data can be evaluated in several ways to provide information about the scattering properties of the sample. The illuminance E of a near-Lambertian light source is

$$E = L_S \cdot \Omega_i \cos \theta_s = L_S \cdot A_i \cos \theta_s / c_s^2 = L_S \cdot \pi r_i^2 \cos \theta_s / c_s^2 \quad (3)$$

where Ω_i is the light source solid angle, A_i the area and r_i the radius of the source aperture i , c_s the aperture-DUT distance, and θ_s the inclination angle of the source to the DUT surface. This is of diagnostic value because the reflectance $\zeta_{Q,i}$ of samples with Lambertian reflection will be proportional to the illuminance $E_{s,i}$. An example is shown in Fig. 2a) for several samples, which are described in 11.12. In this plot, the source area is normalized to the area when the source has a 1° subtense. The samples are labelled based on the scattering components that they exhibit. Sample S has a dominant specular reflection component. Sample SL has a strong specular reflection with some Lambertian scatter. Sample HL exhibits strong haze scatter with some Lambertian scatter. Sample SHL has specular, haze, and Lambertian scatter. Sample L is dominated by Lambertian scatter. In the case of the S and SL samples, direct measurements using the VAS method illustrated in Fig. 2 confirm that the samples are dominated by the specular component since they are independent of source aperture size. In addition, Fig. 2a) confirms that sample L is dominated by the Lambertian component since it is linear with the source aperture area. The influence of haze can be seen in Fig. 2 on the larger source sizes for the HL sample. Therefore, Fig. 2 indicates that if the measured specular reflectance factor depends on the light source size, then the measurement included a significant contribution from diffuse scatter (haze or Lambertian). In that case, the measurement did not reveal the true specular reflectance component.

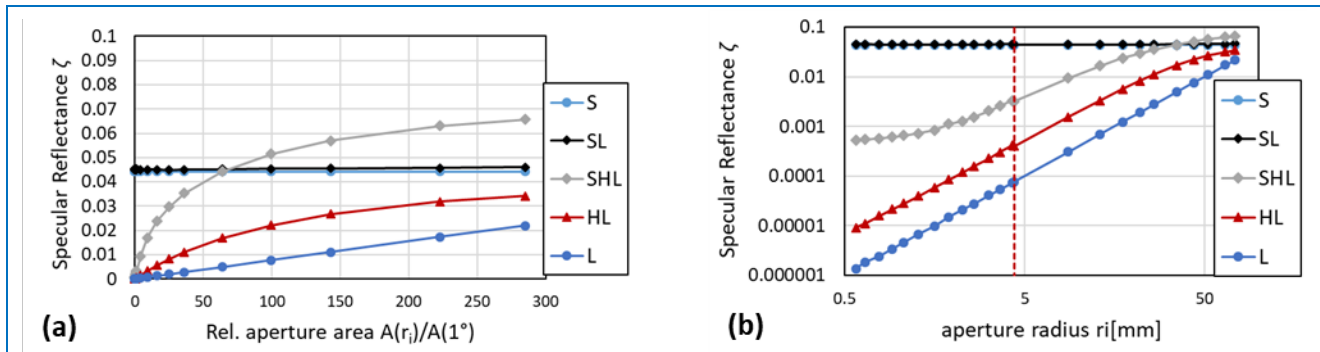


Fig. 2. Direct specular reflection measurements of the diagnostic reflection samples, (a) vs. aperture area in a linear diagram, and (b) vs. aperture radius in a double logarithmic diagram.

The true specular reflectance of the sample can be extracted from the raw data by using the methodology in B17.2. In the limit of small source aperture sizes ($\Psi_i < 1^\circ$ subtense), the luminance scatter profile and BRDF distribution is expected to become relatively flat over small inclination angles. Under this assumption, the reflected luminance L_Q should have the form (see B17.2 for derivation):

$$L_Q = c + a r^2 \quad (4).$$

with

$$\zeta_{Q,corr} = c / L_S \quad (5).$$

$$(R_L + R_h) = a c_s^2 / (\pi L_S \cos \theta_s) \quad (6).$$

where $\zeta_{Q,corr}$ is the true specular reflectance component, R_L is the Lambertian diffuse reflectance, and R_h is the haze reflectance. Therefore, the specular reflectance and the diffuse reflection term ($R_L + R_h$) can be extracted by performing a quadratic fit to the reflected luminance L_Q versus source radius r data (see example data in Figure 3). However, prior to determining the data fitting, it will typically be necessary to perform a correction to the luminance data. In practice, the internal lamp in the light source is held at a constant intensity. Therefore, any change in the source exit aperture will often change the source luminance L_S . This in turn will have a proportional effect on the measured luminance $L_{Q,i}$. However, the formalism in Eq. (4) assumes a constant source luminance. Thus, the reflected luminance must be corrected for source luminance variations. The source luminance for all radii $L_s(r_i)$ were obtained from black glass measurements. Therefore, if a scaling correction $L_s(1^\circ)/L_s(r_i)$ is applied to the measured reflected luminance, then the corrected reflected luminance will scale to constant source luminance at $L_s(1^\circ)$:

$$L_{corr}(r_i) = L(r_i) \cdot L_s(1^\circ) / L_s(r_i) \quad (7).$$



Fig. 3 shows the scaled luminance vs. source aperture radius characteristics $L(r_i)$. The coefficients a and c of the quadratic equation were fit to the convex portion of $L(r_i)$ at very small radii $r_i \leq 3\text{mm}$ following Eq. (4). Using the fitting constant c and Eq. (5), the true specular reflectance ζ was determined for each of the examples in Fig. 3 and summarized in Table 1. An example fit to the SHL sample is shown in Fig. 4. The quadratic fit is only valid at the small apertures where the assumption of a flat (constant) haze distribution can be made.

The quadratic term a was used to estimate the diffuse components ($R_L + R_h$). The example results show the expected values for the haze-free samples S, SL, and L. For samples with haze, the quadratic approximation produces relatively high diffuse reflectance factor values. Since the Lambertian reflectance cannot be much greater than 1, most of the contribution must then come from the haze component.

The reflectance factor is the amount light reflected for a given geometry relative to a perfect Lambertian reflector. Therefore, a value much greater than 1 indicates that more light is reflected in that geometry than would be for a Lambertian reflector. In other words, haze reflectors are gain reflectors. This is analogous to the concept in screen gain in section 16.4 for projection technologies.

Table 1. Specular reflectance and diffuse reflectance factor estimated by fitting a quadratic equation to the measured $L(r_i)$ data.					
	Reflection samples and reflection standards				
	S	SL	SHL	HL	L
ζ	0.044	0.045	$5 \cdot 10^{-4}$	$3 \cdot 10^{-6}$	$6 \cdot 10^{-7}$
$R_L + R_h$	0	0.043	41	5.8	1.048

REPORTING: As needed.

COMMENTS: This is a diagnostic of interest that may be helpful in making investigations and research such as in documenting the effects of haze scatter and documenting the effects of various manufacturing processes. First results

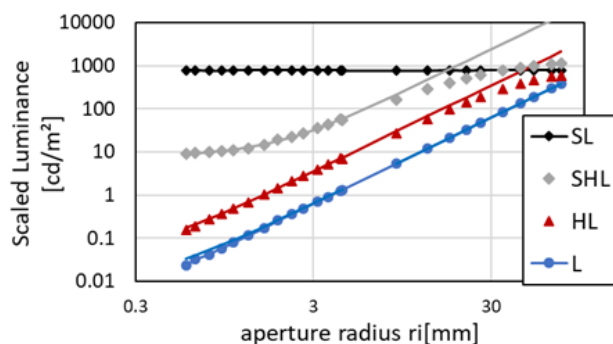


Fig. 3. Reflected luminance vs. aperture radius for example samples; the lines are the quadratic fit.

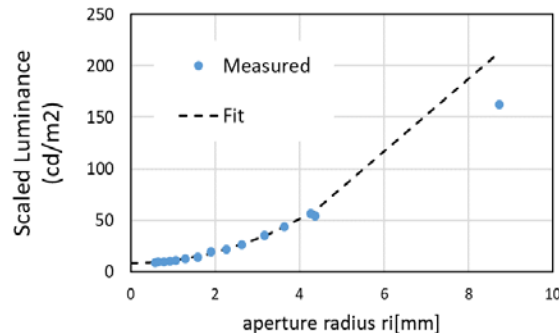


Fig. 4. Example of a quadratic fit for the SHL sample. The fit is only meaningful for small aperture radii.

measured on electrophoretic reflective displays have been reported in.¹

¹ Hertel, D., Kelley, E.F. and Penczek, J. (2020), 64 - 1: Separating Specular Reflection from Diffuse Haze for ePaper Using the Extended Variable - Aperture Source Method. SID Symposium Digest of Technical Papers, 51: 949-952. <https://doi.org/10.1002/sdtp.14028>



11.9 CONTRAST UNDER AMBIENT ILLUMINATION

ALIAS: Ambient Contrast

DESCRIPTION: The purpose of this method is to determine the ambient contrast ratio of a display screen under defined indoor, daylight or other illumination conditions using the display's reflection and transmission coefficients and darkroom luminance. (For reflective displays, the darkroom luminance is zero.) This method calculates the ambient contrast ratio for any combination of hemispherical diffuse and directed sources with the display in a defined orientation and viewed at an arbitrary inclination angle θ_i . The contrast ratio is traditionally defined as the ratio of the white luminance to the black luminance. However, the analysis is the same regardless of the display pattern presented during the reflection and transmission measurement (full screen, highlight, or box). **Units:** None; and **Symbol:** C_A

SETUP: We use the setup conditions associated with the measurement methods under consideration in the previous sections. The ambient contrast ratio is obtained by determining the net display luminance for black L_{ambK} and white L_{ambW} for the particular illumination-detection geometry of interest. Since the image pattern and illumination conditions can significantly affect the ambient contrast ratio, they should be carefully defined and established.

Display Pattern: For full screen ambient contrast ratio, the white luminance, black luminance, reflection and transmission coefficients should be taken with a full white and black screen. (For display patterns follow the guidelines of Chapter 5, for example, § 5.3 and § 5.6 for full-screen white and full-screen black, § 5.10 for full screen contrast, § 5.11 for highlight contrast, and § 5.27 for box contrast.) For highlight ambient contrast ratio, the black luminance and reflection and transmission coefficients should be taken with a full black screen. But the white luminance and reflection and transmission coefficients should be taken with a small white center box on a black background. A 4% white center box is generally used (1/5 the width and height of the active screen).

Illumination Conditions: The illumination/detection geometry should simulate the typical lighting environment in which the display will be used. Table 1 provides typical illumination conditions that the display may be exposed to. If spectral reflection coefficients are measured, then the ambient contrast ratio can also be calculated for a wide range of source spectra.

Table 1: Typical illumination conditions for various environments.

Description of Ambient Condition	Notation	Typical Illuminance at Normal Incidence	Angle of Illumination	Typical Spectra
Night Vision (No moon, clear)	E_{hemi}	0.001 lx	Hemispherical	CIE Illuminant A
Night Vision (Full moon, clear)	E_{dir}	0.1 lx	$\theta_s=45^\circ$	CIE Illuminant A
Residential Street Lighting	E_{dir}	0.5 lx to 3 lx	$\theta_s=35^\circ$	CIE Illuminant A
TV Viewing Room (Diffuse Illum.)	E_{hemi}	60 lx	Hemispherical	CIE Illuminant A, D65 and white LED ¹ LED-BH1
TV Viewing Room (Direct Illum.)	E_{dir}	40 lx	$\theta_s=35^\circ$	CIE Illuminant A, D65 and white LED LED-BH1
Office Space (Diffuse Illum.)	E_{hemi}	200 lx to 500 lx	Hemispherical	CIE Illuminant A, D65 and white LED LED-BH1
Office Space (Direct Illum.)	E_{dir}	200 lx	$\theta_s=35^\circ$	CIE Illuminant A, D65 and white LED LED-BH1
Outdoor (Diffuse Illum.)	E_{hemi}	10,000 lx to 15,000 lx	Hemispherical	CIE Illuminant D65, D75, and higher CCT
Outdoor (Direct Illum.)	E_{dir}	50,000 lx to 100,000 lx	$\theta_s=45^\circ$	CIE Illuminant D50 and D55

PROCEDURE: Determine all the required reflection parameters for each source of illumination employed in the simulation.

ANALYSIS: In most applications, the display will be exposed to both hemispherical diffuse illumination and directed illumination. In the case of outdoor applications, the diffuse component would represent the hemispherical blue sky at a very high CCT (16 kK on the average) and the directed component would come from the sun at about 5500 K CCT. However, since there is only one sun, it could only be on one side of the display. For indoor applications, the diffuse component may

¹ CIE 015:2018 Colorimetry, 4th Ed. (2018).



come from the indirect wall/floor background, and the directed component(s) from one or more luminaires. A directed source could be on either side of the display. Since displays reflect and transmit the incident light in a linear manner, the total light observed from the display surface is a linear combination of light source reflections, transmissions, and the display emission. For the general case of a transparent display with hemispherical diffuse illumination on both sides of the display ($E_{f,hemi}$ and $E_{b,hemi}$), and one directed light source in front and back ($E_{f,dir}$ and $E_{b,dir}$), then the ambient contrast ratio can be calculated using the following equation:

$$C_A = \frac{\pi L_W + \rho_{W,di} E_{f,hemi} + \beta_{Wdir} E_{f,dir} \cos \theta_{f,s} + \tau_{W,di} E_{b,hemi} + T_{Wdir} E_{b,dir} \cos \theta_{b,s}}{\pi L_K + \rho_{K,di} E_{f,hemi} + \beta_{Kdir} E_{f,dir} \cos \theta_{f,s} + \tau_{K,di} E_{b,hemi} + T_{Kdir} E_{b,dir} \cos \theta_{b,s}}, \quad (1)$$

where $\theta_{f,s}$ and $\theta_{b,s}$ are the front and back incidence angles for the directed illumination, $\rho_{W,di}$ and $\rho_{K,di}$ are the hemispherical reflectance values with specular included for a white and black display pattern, β_{Wdir} and β_{Kdir} are the luminance factors of the directed source for a white and black display pattern, $\tau_{W,di}$ and $\tau_{K,di}$ are the hemispherical transmittance with specular included for a white and black display pattern, and T_{Wdir} and T_{Kdir} are the transmittance factors of the directed source for a white and black display pattern. By using the hemispherical illumination with specular included, Eq. (1) assumes that the illumination in the specular/regular direction is the same as the rest of the hemispherical background. This would be equivalent to viewing the display outdoors with the blue sky in the specular direction. However, if the display is tilted so that the user's body is viewed in the specular direction, its illumination can be significantly different from the hemispherical background. In this latter case, hemispherical illumination with specular excluded may be more appropriate:

$$C_A = \frac{\pi L_W + \rho_{W,de} E_{f,hemi} + \beta_{Wspec} E_{spec} \cos \theta_{f,s} + \beta_{Wdir} E_{f,dir} \cos \theta_{f,s} + \tau_{W,di} E_{b,hemi} + T_{Wdir} E_{b,dir} \cos \theta_{b,s}}{\pi L_K + \rho_{K,de} E_{f,hemi} + \beta_{Kspec} E_{spec} \cos \theta_{f,s} + \beta_{Kdir} E_{f,dir} \cos \theta_{f,s} + \tau_{K,di} E_{b,hemi} + T_{Kdir} E_{b,dir} \cos \theta_{b,s}}, \quad (2)$$

where the hemispherical reflectance with specular excluded $\rho_{W,de}$ and $\rho_{K,de}$ are used in addition to the directed source luminance factors β_{Wspec} and β_{Kspec} , which represents the reflected contribution from illumination E_{spec} in the front specular direction. In the case where the specular reflectance is known we can re-write Eq. (2) to account for the specular reflectances $\zeta_W(\theta_c)$, $\zeta_K(\theta_c)$, and the luminance L_{spec} in the specular direction θ_c :

$$C_A = \frac{\pi L_W + \rho_{W,de} E_{f,hemi} + \zeta_W(\theta_c) L_{spec} + \beta_{Wdir} E_{f,dir} \cos \theta_{f,s} + \tau_{W,di} E_{b,hemi} + T_{Wdir} E_{b,dir} \cos \theta_{b,s}}{\pi L_K + \rho_{K,de} E_{f,hemi} + \zeta_K(\theta_c) L_{spec} + \beta_{Kdir} E_{f,dir} \cos \theta_{f,s} + \tau_{K,di} E_{b,hemi} + T_{Kdir} E_{b,dir} \cos \theta_{b,s}} \quad (3)$$

Additional terms for the directed reflected and transmitted components can be added if multiple directed sources are present and their reflection and transmission coefficients have been determined. For opaque displays, the transmission coefficients would be zero. For reflective displays, $L_W = L_K = 0$.

REPORTING: In addition to the ambient contrast ratio, report all of the values used in equation (1) or (2). Also report the illumination-detection geometry, the display pattern used, and the CCT of the illumination sources.

COMMENTS: (1) Geometries: Care should be taken to ensure that the darkroom luminance measurements and reflection coefficients use consistent illumination-detection geometries and display patterns for a given ambient contrast ratio calculation. The hemispherical illumination geometry with specular excluded can be very sensitive to the display reflection and transmission properties and alignment errors. If the display has a significant haze component or exhibits matrix scatter, then the hemispherical illumination with specular included is recommended.

(2) Simulation of and Scaling to Daylight, Sunlight, and Skylight Conditions: Three specific types of illumination are defined in this document for daylight situations:

- a. Sunlight:** Direct sunlight falling on the surface of the display. We will assume $E_{sun} \cong 100\,000$ lx to be the illuminance that is projected at an angle θ from the vertical so that the illuminance on a screen is $E_{sun} \cos \theta$. Often we use a value of $\theta = 45^\circ$.
- b. Skylight:** Light from the sky, clouds, ground, etc., but not directly from the sun. We will assume $E_{sky} = 10\,000$ lx to 15 000 lx.
- c. Daylight:** This is a combination of direct skylight and direct sunlight: $E_{day} = E_{sky} + E_{sun} \cos \theta$.

Thus to claim a daylight ambient contrast or daylight readability, the reflection parameters must be measured with a uniform source simulating the skylight, and with a collimated or small directed source (collimated preferred) simulating the sunlight. The reflected and transmitted luminance scale linearly with these illuminance levels.



Analysis example	
Darkroom display white luminance L_W (cd/m ²)	250
Darkroom display black luminance L_K (cd/m ²)	0.1
Hemispherical reflectance of white screen $\rho_{W,di}$	0.025
Hemispherical reflectance of black screen $\rho_{K,di}$	0.023
Front hemispherical diffuse illuminance $E_{f,hemi}$ (lx)	15,000
Luminance factor of directed illumination for white screen β_{Wdir}	0.00061
Luminance factor of directed illumination for black screen β_{Kdir}	0.00059
Front directed illuminance $E_{f,dir}$ (lx)	65,000
Front incident angle of directed illumination $\theta_{f,s}$	45°
Hemispherical transmittance of white screen $\tau_{W,di}$	0.13
Hemispherical transmittance of black screen $\tau_{K,di}$	0.00018
Back hemispherical diffuse illuminance $E_{b,hemi}$ (lx)	15,000
Back directed illuminance $E_{b,dir}$ (lx)	0
Ambient contrast ratio C_A	8.4



11.9.1 ESTIMATED CONTRAST UNDER AMBIENT ILLUMINATION

CAUTION: The adjustment of light source illuminance can make this method prone to color and illuminance drift.

ALIAS: Estimated Ambient Contrast

DESCRIPTION: This photometric method describes a direct measurement that estimates the ambient contrast ratio of a display for a defined source-detector geometry with a fixed level of illumination. This measurement is intended for quick contrast-ratio measurements using a single illumination setup and cannot be extended to other illumination levels. **Units:**

None; and **Symbol:** C_A

SETUP: Determine the ambient illumination conditions appropriate to the task that is to be simulated and replicate them with appropriate lighting.

PROCEDURE:

1. Allow the display to fully warm up and prepare the display to sequentially exhibit white (either full screen or box) and black full screen.
2. Adjust the illumination of a hemispherical background E_{hemi} and the illumination levels of each directed source to the required illuminances E_i for $i = 1, 2, \dots, n$ directed sources. Allow time for all sources to stabilize and check the illumination levels. (Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.) The illuminances should be measured using an illuminance meter with good cosine correction. The directed sources can be adjusted and checked in an additive manner by shuttering each source with an opaque black card. Avoid allowing your body to contribute to the illuminance measurement.
3. Measure the same white and black display screens as in step 1 only under the required ambient illumination conditions to obtain L_{ambW} and L_{ambK} . Be sure that the illuminance doesn't change with a change in screen patterns. We assume that changes in the display screen from white to black do not affect the sources.

ANALYSIS: The ambient contrast for this very specific illumination condition is given by:

$$C_A = \frac{L_{\text{ambW}}}{L_{\text{ambK}}} \quad (1)$$

Note: This measurement of ambient contrast ratio is only valid for this particular source-detector geometry and arranged illuminances.

REPORTING: Report the source-detector geometry used, a description of the light source spectra, the orientation of the display, the white screen pattern used (full screen or center box), the ambient contrast ratio value, the white and black screen luminance, the white and black screen illuminance, and the target illuminance. The report should also describe the method used to obtain the display illuminance.

COMMENTS: It is generally recommended that hemispherical illumination (with specular included) be used for this method since it is the most robust. Clearly, we would prefer people measure the reflection parameters carefully and perform an ambient contrast determination based upon more carefully measured quantities.



11.10 COLOR UNDER AMBIENT ILLUMINATION

ALIAS: Ambient Color

DESCRIPTION: The purpose of this method (a calculation) is to determine the ambient color of a display screen under defined illumination conditions using the display's spectral reflection and transmission coefficients and darkroom spectral radiances. (For reflective displays the darkroom spectral radiance and luminance are zero.) This method calculates the ambient color for hemispherical illumination and any combination of directed sources with the display in a defined orientation and viewed at an arbitrary detector inclination angle θ_d . The display color is traditionally measured with a full screen. However, for emissive displays the ambient color is dependent on the magnitude of the darkroom display spectral radiance relative to the ambient light, which may be a function of the color pattern size. The analysis is the same regardless of the display pattern presented (full screen, highlight, box) during the reflection measurement. **Units:** None; and **Symbol:** CIE 1931 x and y chromaticity

SETUP & PROCEDURE: The ambient display color is calculated using the display's darkroom spectral radiance $L_{Q0d}(\lambda)$ at the maximum color level, the spectral reflection coefficients for the particular color Q as measured using the methods in this chapter, full screen or center color box pattern, and detector inclination angle θ_d of interest. A spectroradiometer with a maximum bandwidth of 10 nm should be used for spectral measurements. If the light source spectral distribution has significant structure, the use of a smaller bandwidth like 5 nm is recommended.

Display Pattern: When the spectral reflection and transmission coefficients are independent of the size of the color patch used in the measurement, then a full screen or small center box at the desired color (see chapter 5) can be used. However, if the spectral reflection and transmission coefficients are dependent on the size of the color patch, or the image content surrounding the center measurement area, then the test pattern shown in Figure 1 should be used for the reflection and transmission measurements. In addition, if the display darkroom luminance is found to depend on the test pattern, then the darkroom luminance of the desired colors should also be measured using the test pattern in Figure 1.

The concept in Figure 1 is to maintain the pre-gamma average pixel level (APL) at 25 % independent of what center color is being measured. Each of the nine large boxes have 2/9 the width and height of the active display screen area. The only box that is measured is the center box. Most of the other surrounding boxes are held constant to sample the display gamut uniformly over the screen. There is a smaller grey box (in this example) that is intended to be the input digital compliment of the code value of the center box color. For displays that are sensitive to APL loading effects, the small grey box is used to maintain the APL loading for different center colors. In the color example shown, the center box has an 8-bit RGB digital code value of (192,192,192), and the small gray box has the 8-bit complimentary color (63,63,63). If the center box was changes to a mid-level cyan, such as (200,200,200), then the small box color would change to (55,55,55). If the display is not sensitive to APL loading, then this small gray box can remain a constant black color.

Illumination Conditions: The use of reflection and transmission coefficients enables the ambient display color to be calculated at any desired illumination level for the same illumination-detection geometry. Table 1 in the previous section provides typical illumination conditions that the display may be exposed to. A knowledge of the hemispherical spectral reflectance factor $[R_{Qdi/\theta d}(\lambda)$ or $R_{Qde/\theta d}(\lambda)]$, hemispherical spectral transmittance factor $[T_{Qdi/\theta d}(\lambda)$ or $T_{Qde/\theta d}(\lambda)]$, the spectral reflectance factor $R_{Q0s/\theta d}(\lambda)$ and spectral transmittance factor $T_{Q0s/\theta d}(\lambda)$ for directed sources is required in order to calculate the ambient display color for a wide variety of source spectra. The detailed procedures for measuring these spectral reflectance factors at a given detector inclination angle θ_d and light source inclination θ_s and azimuth angle ϕ_s are described in this chapter. For opaque displays (like conventional LCDs), the transmittance factors are zero. For reflective displays, the darkroom spectral radiance $L_{Q0d}(\lambda) = 0$.

ANALYSIS: The color of a display under ambient illumination is determined by a summation of the display's intrinsic light emission and any reflected and transmitted ambient light. In most applications, the display will be exposed to both hemispherical illumination and directed illumination. In the case of outdoor applications, the hemispherical illumination would represent the blue skylight and the directed component would come from the sun. For indoor applications, the hemispherical illumination may come from the indirect wall/floor background, and the directed component(s) from one or

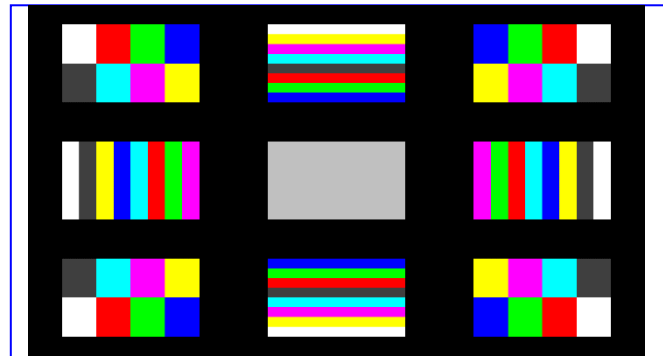


Fig. 1. Multi-color test pattern with medium content loading.



more luminaires. Since most displays reflect and transmit the incident light in a linear manner, the total light observed from the display surface is a linear combination of light source reflections, transmissions, and the display emission.

Hemispherical illumination with specular included: If a hemispherical illumination source (with specular included) of spectral irradiance $E_{f,hemi}(\lambda)$ and $E_{b,hemi}(\lambda)$ in front and back of the display, and one directed source of spectral irradiance $E_{f,dir}(\lambda)$ and $E_{b,dir}(\lambda)$ in front and back, then the total spectral radiance observed from the display at a given color Q and viewing inclination angle θ_d in that ambient environment can be calculated using the following equation:

$$L_{Qamb\theta_d}(\lambda) = L_{Q\theta_d}(\lambda) + \frac{R_{Qdi/\theta_d}(\lambda)E_{f,hemi}(\lambda)}{\pi} + \frac{R_{Q\theta_s/\theta_d}(\lambda)E_{f,dir}(\lambda)\cos\theta_{f,s}}{\pi} + \frac{T_{Qdi/\theta_d}(\lambda)E_{b,hemi}(\lambda)}{\pi} + \frac{T_{Q\theta_s/\theta_d}(\lambda)E_{b,dir}(\lambda)\cos\theta_{b,s}}{\pi} \quad (1)$$

where θ_s is the angle of incidence for the directed illumination, $R_{Qdi/\theta_d}(\lambda)$ is the spectral hemispherical reflectance factor with specular included for a given display color pattern, $T_{Qdi/\theta_d}(\lambda)$ is the spectral hemispherical transmittance factor with specular included, $R_{Q\theta_s/\theta_d}(\lambda)$ is the spectral reflectance factor and $T_{Q\theta_s/\theta_d}(\lambda)$ is the spectral transmittance factor for a directed source.

Hemispherical illumination with specular excluded: If a specular excluded hemispherical illumination geometry is used, then the total spectral radiance observed from the display is calculated using the following relation:

$$L_{Qamb\theta_d}(\lambda) = L_{Q\theta_d}(\lambda) + \frac{R_{Qde/\theta_d}(\lambda)E_{f,hemi}(\lambda)}{\pi} + \frac{R_{Q\theta_d/\theta_d}(\lambda)E_{spec}(\lambda)\cos\theta_{f,s}}{\pi} + \frac{R_{Q\theta_s/\theta_d}(\lambda)E_{f,dir}(\lambda)\cos\theta_{f,s}}{\pi} + \frac{T_{Qde/\theta_d}(\lambda)E_{b,hemi}(\lambda)}{\pi} + \frac{T_{Q\theta_d/\theta_d}(\lambda)E_{reg}(\lambda)\cos\theta_{b,s}}{\pi} + \frac{T_{Q\theta_s/\theta_d}(\lambda)E_{b,dir}(\lambda)\cos\theta_{b,s}}{\pi} \quad (2)$$

where $R_{Qde/\theta_d}(\lambda)$ is the spectral reflectance factor for hemispherical illumination with specular excluded, $T_{Qde/\theta_d}(\lambda)$ is the spectral transmittance factor for hemispherical illumination with regular excluded, $R_{Q\theta_d/\theta_d}(\lambda)$ the spectral reflectance factor and $E_{spec}(\lambda)$ the spectral irradiance are used to simulate the contribution of a source reflected in the specular direction, and $T_{Q\theta_d/\theta_d}(\lambda)$ is the spectral transmittance factor and $E_{reg}(\lambda)$ the spectral irradiance are used to simulate the contribution of a source transmitted in the regular direction.

It is critical that all terms use geometries having the same viewing direction and display orientation. For opaque displays (like conventional LCDs), the transmittance factors are zero. For reflective displays, the darkroom spectral radiance $L_{Q\theta_d}(\lambda) = 0$. The relative spectral irradiance distribution of daylight illuminants at a given CCT can be obtained using Equation (8) and Table 1 in the introduction section.



The ambient chromaticity of a display at a given color state (e.g. Q= white, black, red, green, or blue) under defined illumination conditions is determined by its equivalent ambient tristimulus values. These values can be calculated from the total spectral radiance determined in Equation (1) or (2) using the following relations:

$$X_{Q_{amb}} = 683 \int_{\lambda} L_{Q_{amb}}(\lambda) \bar{x}(\lambda) d\lambda \quad (3)$$

$$Y_{Q_{amb}} = 683 \int_{\lambda} L_{Q_{amb}}(\lambda) \bar{y}(\lambda) d\lambda \quad (4)$$

$$Z_{Q_{amb}} = 683 \int_{\lambda} L_{Q_{amb}}(\lambda) \bar{z}(\lambda) d\lambda \quad (5)$$

where $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the color matching functions (see CIE 15). The ambient 1931 CIE x and y chromaticity coordinates of the emitting display under the defined ambient illumination conditions are then given by:

$$x = \frac{X_{Q_{amb}}}{X_{Q_{amb}} + Y_{Q_{amb}} + Z_{Q_{amb}}} \quad (6)$$

$$y = \frac{Y_{Q_{amb}}}{X_{Q_{amb}} + Y_{Q_{amb}} + Z_{Q_{amb}}} \quad (7)$$

The CIE 1931 chromaticity coordinates can also be transformed to the CIE 1976 chromaticity coordinates using the transformation defined in CIE publication 15.

REPORTING: In addition to the ambient display color chromaticity coordinates, report the darkroom luminance and chromaticity, the spectral or luminous reflection and transmission coefficients, and the illuminance and CCT of the hemispherical diffuse and directed sources. Also report the display pattern, orientation, and illumination-detection geometry used.

COMMENTS: Care should be taken to ensure that the darkroom luminance measurements, reflection coefficients, and transmission coefficients use consistent illumination/detection geometries and display patterns for a given ambient display color calculation. The ambient color gamut can be obtained by determining the ambient display color for all the primaries. The hemispherical illumination geometry with specular excluded can be very sensitive to the display reflection and transmission properties and alignment errors. If the display has a significant haze component, or exhibits matrix scatter, then the hemispherical illumination with specular included is recommended.

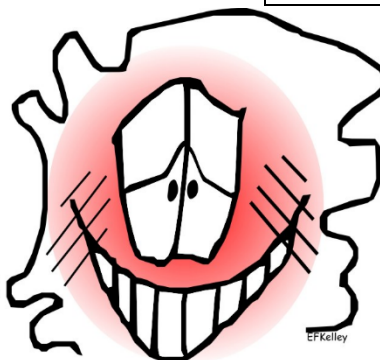
—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example

Darkroom display blue luminance L_B (cd/m ²)	32
Darkroom display blue luminance CIE 1931 chromaticity	x= 0.141 y= 0.056
Hemispherical diffuse reflectance factor of blue screen $R_{Qdi/\theta d}$	0.023
CCT of front hemispherical diffuse illumination (K)	7500
Front hemispherical diffuse illuminance $E_{f,hemi}$ (lx)	15,000
Reflectance factor of directed illumination for blue screen $R_{Qos/\theta d}$	0.00059
CCT of front directed illumination (K)	5000
Front directed illuminance $E_{f,dir}$ (lx) at normal incidence	65,000
Inclination angle of directed illumination $\theta_{f,s}$	45°
Back hemispherical diffuse illuminance $E_{b,hemi}$ (lx)	1,500
CCT of back hemispherical diffuse illumination (K)	5000
Hemispherical diffuse transmittance factor of blue screen $T_{Qdi/\theta d}$	0.040
Back directed illuminance $E_{b,dir}$ (lx) at normal incidence	0
Ambient display color of blue screen (CIE 1931 chromaticity)	x = 0.208 y = 0.173

Um... The contrast of the display went up a factor of ten when we used a replica mask. Um... have you sent those results out yet???





11.10.1 GRAY SCALE UNDER AMBIENT ILLUMINATION

ALIAS: Ambient Gray Scale

DESCRIPTION: The purpose of this method is to determine the ambient grayscale (including grayscale data for each separately addressable primary color, usually R, G, B) of a display screen under defined indoor, daylight or other illumination conditions using the display's spectral reflection coefficients, spectral transmission coefficients, and darkroom spectral radiance. This method calculates the ambient grayscale for any combination of hemispherical diffuse and directed sources with the display in a defined orientation and viewed at an arbitrary inclination angle θ_d . The display grayscale is traditionally measured with a full screen. However, the grayscale may be dependent on the display pattern (due to loading or automatic dimming functions). The analysis is the same regardless of the display pattern presented (full screen or other pattern) during the reflection and transmission measurements. **Units:** cd/m^2 ; and **Symbol:** L or Y and CIE 1931 x and y chromaticity

ADDITIONAL SETUP & PROCEDURE: For each gray shade, the ambient display performance is calculated using the display's darkroom spectral radiance $L_Q(\lambda)$ at the corresponding gray shade, and the spectral reflection and transmission coefficients for the particular color Q and pattern size of interest. A spectroradiometer will be needed for these measurements.

Display Pattern: At a minimum, the ambient display grayscale measurement will require 9 levels of gray (for white to black or for each color to black). The display should be set to the desired pattern (full screen or center box with black background, see chapter 5), and the spectral radiance measured in the center of the display at the desired gray scale. The measurements should be made using evenly spaced gray levels (for example from white to black). In the case of 9 gray levels with interval of 32 the corresponding gray levels are 0, 31, 63, 95, 127, 159, 191, 223 and 255. For reflective displays the darkroom luminances will be zero

ANALYSIS: Same as main ambient display color section. The total ambient spectral radiance, luminance, and chromaticity coordinates are to be calculated for each gray level of interest. If the display's reflection or transmission properties change with gray level, then the appropriate reflection and transmission coefficients need to be used for each gray level.

REPORTING: For each ambient gray scale calculation, report the luminance response and color coordinates at each gray level. In addition, for each gray level, report the darkroom luminance, chromaticity, the luminous reflection coefficients, the luminous transmission coefficients, the illuminance and CCT of the hemispherical diffuse and directed sources. Also report the illumination/detection geometry and the display pattern used.

Note: One may also analyze this gray scale data with the analysis techniques presented in the gamma/grayscale section with the exception of analysis techniques which subtract the luminance level for zero digital input level as these "black level" luminances can be quite large in ambient conditions.

COMMENTS: Care should be taken to ensure that the darkroom measurements, reflection coefficients, and transmission coefficients use consistent illumination/detection geometries, gray levels, and display patterns for a given ambient display gray pattern calculation.

—SAMPLE DATA ONLY—								
Do not use any values shown to represent expected results of your measurements.								
Reporting – Sample Analysis				E_{hemi}	E_{dir}	$CCT(\text{hemi})=5000K$ $CCT(\text{dir})=5000K$		
	Darkroom Measurement			400 lx	200 lx	Ambient Grayscale Calculation		
Level	Y (cd/m^2)	x	y	$R_{Q\text{di}/\theta_d}$	$R_{Q\theta_s/\theta_d}$	Y (cd/m^2)	x	y
White(9) -255	197.5	0.314	0.330	0.08	0.03	209.6	0.318	0.328
Level 8	144.5	0.320	0.337	0.08	0.03	156.6	0.320	0.329
Level 7	104.2	0.316	0.332	0.08	0.03	116.3	0.321	0.329
Level 6	71.3	0.318	0.338	0.08	0.03	83.4	0.322	0.330
Level 5	46.9	0.316	0.334	0.08	0.03	59.0	0.324	0.331
Level 4	27.4	0.318	0.337	0.08	0.03	39.5	0.326	0.333
Level 3	13.5	0.321	0.333	0.08	0.03	25.6	0.331	0.337
Level 2	4.1	0.322	0.335	0.08	0.03	16.2	0.338	0.343
Black (1)-0	0.3	0.315	0.333	0.08	0.03	12.4	0.345	0.358



11.10.2. Color Gamut Envelope for Reflective Displays - Color Capability

DESCRIPTION

The color gamut of a display can be realized as a three-dimensional volume, ranging from the display white at the top, outward to its most saturated colors, and then further downward to the display's black point (see Section 5.32). An appropriate sampling of a reflective display's colors under defined illumination represented in the CIELAB color space can provide a good estimate of the display's color capability. For emissive and transmissive displays where the user is adapted to the light produced by the display, the method for determining the color capability of the display is described in section 5.32. The evaluation of a reflective display's color capability is different and is explained in this section. This section describes the proper way to measure the Color Gamut Envelope for reflective displays, then the remaining analysis methods defined in 5.32 can be used for evaluating the color gamut volume and visualizing the gamut with the gamut rings diagram. This method should be applied for reflective displays without a frontlight, or the frontlight is turned off.

Unit: ΔE^3 ; and symbol: None.

Reflective color displays are fundamentally different from emissive color displays. Unlike emissive displays, where colors are perceived relative to the display illuminant, reflective displays typically follow the print industry, where colors are perceived relative to a reference illuminant reflected from an ideal white reflecting diffuser.

Viewing environments and reference white

Emissive color displays are usually measured under darkroom conditions when evaluating their maximum color capability, because ambient light reflections only degrade their color performance. An emissive display in the darkroom is seen in isolation; the display's own white is the illuminant to which all colors are referred to. Reflective displays require illumination; they are in an illuminated ambient environment where they are viewed not in isolation but surrounded by, and its colors judged against, other equally illuminated objects. In a multisource ambient illumination environment, the color of the illuminant becomes apparent when reflected from an ideal white reflecting diffuser. For example, freshly fallen snow, being close to ideal white and Lambertian, will show the color of any illuminant it reflects, be it natural, artificial or any combination thereof. Therefore, the ambient illuminant, reflected from an ideal white reflecting diffuser, is referred to as the reflective white reference. For the reflective display, lightness and chroma of a reflective color are normally defined relative to that of a reflective white reference, for example an ideal white reflecting diffuser under the same ambient illumination. In real life, the white reference can be simply a stack of white paper. In metrology, it will be represented by a diffuse white reflectance standard against which the maximum display white will be evaluated.

Color measurements

In order to obtain an accurate representation of the display's color gamut, a relatively dense sampling of the display's colors are measured by rendering 602 evenly distributed points in the RGB signal space (see 5.32). The spectral reflectance factor of each rendered color under hemispherical diffuse (11.2) or 45/0 right-light illumination (11.5) can be determined using the spectral equivalent of the procedures in those corresponding sections. Once the reflection coefficients are determined, the predicted color that will be obtained for a given illumination level and spectra (see Table 1 in 11.9) is described by the analysis in section 11.10. The same analysis can be used to determine the predicted color for a single illumination source (hemispherical or ring-light), or the combination of the two. The result will be a set of ambient tristimulus values and chromaticity coordinates for predicted color. To obtain the reference white for the reflective display, an ideal white reflecting diffuser is subjected to the same measurements as the display, and its spectral radiance determined for each illumination geometry.



Color gamut envelope

To determine the display's color capability, the predicted ambient tristimulus values need to be transformed into the perceptually uniform CIELAB color space. For reflective displays, the predicted ambient tristimulus values of the ideal white reflecting diffuser is used as the reference white. The chromatic adaptation transform needed to transform the predicted tristimulus values of the ambient illuminant reflected by the white reflecting diffuser to a D50 white is used on all the predicted display tristimulus values to adapt them to the same white point (see 5.32). Section 5.32 also describes the analysis for transforming the adapted tristimulus values to CIELAB $L^*a^*b^*$ values. These $L^*a^*b^*$ values define the color gamut envelope of the reflective display. Once this envelope is determined, the analysis in 5.32 can be used to calculate the CIELAB color gamut volume and visualize the gamut rings diagram.

SETUP



This method obtains reflection coefficients for a reference illuminant condition that can contain both hemispherical diffuse illumination (11.2) and 45/0 ring-light illumination (11.5). Each reflection measurement is performed with a single light source. The analysis for the combined illumination configuration is described in 11.10, where some suggested illumination levels and spectra are given in Table 1 of 11.9.

APPLICATION

This measurement can be applied to reflective displays. If the reflective display has an emissive component, for example from an integrated front light, it will be set to zero by turning all light sources contributing to the display's emissive component off. If the reflective display has a transmissive component, all illumination sources contributing to the display's transmissive component will be turned off.

PROCEDURE

The color of a display at a given color state Q ($Q = R, G, B, C, M, Y, K, \dots$) under defined ambient illumination conditions is determined by its equivalent ambient tristimulus values $X_{Q,amb}$, $Y_{Q,amb}$, and $Z_{Q,amb}$.

Determining these ambient tristimulus values requires the following procedural steps:

1. **Selecting the set of RGB input colors:** The reference method of Section 5.32 uses a predefined set of 602 colors on the surface of the gamut solid that provide adequate coverage to create an accurate estimate of the gamut envelope. The set of 602 colors is achieved by subdividing each face of the color cube into a regular grid of 11×11 colors. The number of grid points should be chosen according to the capability of the display to reproduce color levels. For example, if the display is known to reproduce no more than 5 image levels then it might be sufficient to subdivide the input color into a 5×5 grid. In most cases it is advisable to choose a higher RGB grid density to ensure an adequate density of displayed CIELAB color samples.
2. **Measuring the spectral reflectance factors for each display color Q ,** using the traditional full-screen pattern or the pattern specified in Section 5.32, Figure 2, and the illumination-detection geometry specified for each ambient illumination component. The chosen illumination configuration should be based on the intended application of the reflective display. Outdoor and indoor applications can have both hemispherical diffuse and directed illumination components. The incident angle of the light source θ_s should also mimic the expected conditions under use. For the purpose of color capability, the viewing direction of the detector should be near normal, $\theta_d = 0$. In most cases, two reflectance measurements should be sufficient for determining color capability under ambient illumination: spectral reflectance $\rho_{Q,di/0}(\lambda)$ under hemispherical diffuse illumination (specular included) according to Section 11.2, and spectral reflectance factor $R_{Q,45/0}(\lambda)$ under directed 45°/0° ring-light illumination according to Section 11.5.



3. **Measuring the spectral reflectance and reflectance factors for the diffuse white reflectance standard** (the ideal white reflecting diffuser) using the same illumination-detection geometry specified for each ambient illumination component as used for the display. The results are the spectral reflectance $\rho_{\text{std,di}/0}(\lambda)$ under hemispherical diffuse illumination (specular included), and spectral reflectance factor $R_{\text{std,45}/0}(\lambda)$ under directed $45^\circ/0^\circ$ ring-light illumination.

ANALYSIS

The following steps outline the process from measured spectral reflectance and reflectance factors to the 3D representation of the gamut volume envelope.

1. Calculate the total spectral radiance according to section 11.10 for each display color Q from their measured spectral reflectance, spectral reflectance factors, and the illumination conditions for the desired ambient viewing environment. The spectral radiance of the diffuse white reflectance standard $L_{\text{std}}(\lambda)$ is calculated in a similar fashion but using a spectral reflectance and spectral reflectance factor value of 1. Illumination conditions are specified as spectral irradiance $E(\lambda)$, calculated from illumination spectra, *e.g.*, illuminant spectra such as A, D50, D65, D75 tabulated in CIE 015, and some suggested illumination levels in units of lux to which these illumination spectra are to be scaled (see Table 1 in 11.9). In case no ambient illumination conditions are specified, spectral radiance is calculated for the CIE D50 illuminant from the measured spectral reflectance $\rho_{Q,\text{di}/8}(\lambda)$ under hemispherical diffuse illumination (specular included) having the spectral irradiance $E_{\text{D50hemi}}(\lambda)$

$$L_{Q,\text{di}/8}(\lambda) = \frac{\rho_{Q,\text{di}/8}(\lambda) E_{\text{D50hemi}}(\lambda)}{\pi} \quad (11.1)$$

and from the measured spectral reflectance factor $R_{Q,45/0}(\lambda)$ under directed $45^\circ/0^\circ$ ring-light illumination having the spectral irradiance $E_{\text{D50dir}}(\lambda)$.

$$L_{Q,45/0}(\lambda) = \frac{R_{Q,45/0}(\lambda) E_{\text{D50dir}}(\lambda)}{\pi} \quad (11.2)$$

Similarly, spectral radiance under generic indoor ambient D50 illumination can be calculated:

$$L_{Q,\text{amb}}(\lambda) = \frac{\rho_{Q,\text{di}/8}(\lambda) E_{\text{D50hemi}}(\lambda)}{\pi} + \frac{R_{Q,45/0}(\lambda) E_{\text{D50dir}}(\lambda)}{\pi} \quad (11.3)$$

2. The tristimulus values ($X_{Q,\text{amb}}$, $Y_{Q,\text{amb}}$, $Z_{Q,\text{amb}}$) of each reflected display color Q under ambient illumination are calculated following Equations (3), (4), and (5) in Section 11.10. The tristimulus values ($X_{\text{std,amb}}$, $Y_{\text{std,amb}}$, $Z_{\text{std,amb}}$) of the diffuse white reflectance standard under the same ambient illumination are calculated in a similar way but using a spectral reflectance and spectral reflectance factor value of 1.
3. **Chromatic adaptation to a common D50 white point** of all tristimulus values $X_{Q,\text{amb}}$, $Y_{Q,\text{amb}}$, $Z_{Q,\text{amb}}$ is performed if the illuminant spectra are other than D50, or if different illuminant spectra were used for the hemispherical and directional components of ambient illumination. See section 5.32 for the chromatic adaptation calculation.
4. **The CIELAB values** of each reflected display color Q , $L_{Q,\text{amb}}^*$, $a_{Q,\text{amb}}^*$, and $b_{Q,\text{amb}}^*$ are calculated from the adapted tristimulus values, where the reference white point is D50:

$$L_{Q,\text{amb}}^* = 116 \cdot f\left(\frac{Y_{Q,\text{amb}}}{Y_{\text{std,amb}}}\right) - 16 \quad (11.4)$$

$$a_{Q,\text{amb}}^* = 500 \left[f\left(\frac{X_{Q,\text{amb}}}{X_{\text{std,amb}}}\right) - f\left(\frac{Y_{Q,\text{amb}}}{Y_{\text{std,amb}}}\right) \right]$$



$$b_{Q,amb}^* = 200 \left[f \left(\frac{Y_{Q,amb}}{Y_{std,amb}} \right) - f \left(\frac{Z_{Q,amb}}{Z_{std,amb}} \right) \right]$$

with

$$f(t) = \begin{cases} t^{\frac{1}{3}} & t > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3} \left(\frac{29}{6}\right)^2 t + \frac{16}{116} & \text{otherwise} \end{cases}$$

The transformation of the 602 adapted tristimulus values to CIELAB colors creates the necessary data to create the color gamut envelope for the reflective display. When the CIELAB colors are properly formatted in the CGATS 17 Format 2 Color Data Standard as specified in 5.32, the analysis in section 5.32.1 through 5.32.3 can be used to calculate the CIELAB color gamut volume, intersection, and visualize the color gamut rings diagram.

An example transformation from 602 input colors on the faces of the RGB signal cube, and the corresponding envelope colors of a hypothetical reflective display are shown in FIGURE 11.1. Examples of color gamut volume and gamut ring diagrams are given in FIGURE 11.2 and FIGURE 11.2.

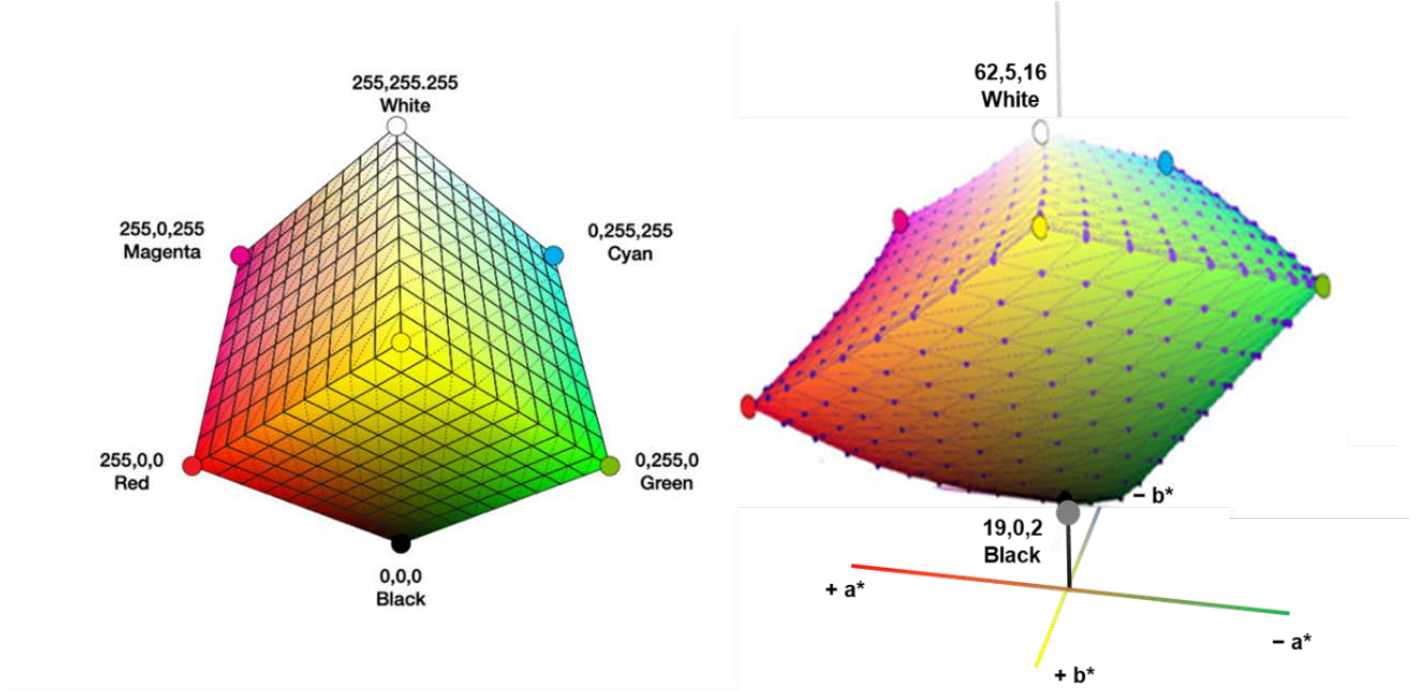


FIGURE 11.1. On the left is the linear unbounded RGB signal space (8 bit) tessellated by 602 evenly distributed points on its surface. On the right is the response of a hypothetical reflective color display to the 602 test points in the CIE 1976 $L^*a^*b^*$ color space using the same tessellation.

REPORTING

Report the measured color gamut envelope data, preferably in the CGATS 17 format described in 5.32. It is also desirable to use the analysis in sections 5.32.1 through 5.32.3 to calculate the CIELAB color gamut volume (in units of ΔE^3) and create the color gamut rings diagram. The illumination conditions should also be reported.

COMMENTS

The CIELAB envelope of the reflective display shows some fundamental differences to that of an emissive display shown in FIGURE 1 of 5.32. In the reflective display example shown above, the display white at $L^* = 62$ is lower than 100 and



is chromatic (not neutral) due to optical reflection losses and the spectral properties of the electrophoretic white pigment materials. The display black at $L^* = 19$ is higher than zero due to incomplete spectral absorption of the electrophoretic color pigment materials. The examples shown in FIGURE 11.2 were measured on actual electrophoretic color displays using two alternative color technologies to display the 602 sample colors: (a) four pigments (scattering white and absorbing cyan, magenta, yellow) with a color gamut volume of 15,800 vs. (b) black & white display with color filter array having red, green, blue subpixels with a color gamut volume of only 3,100.

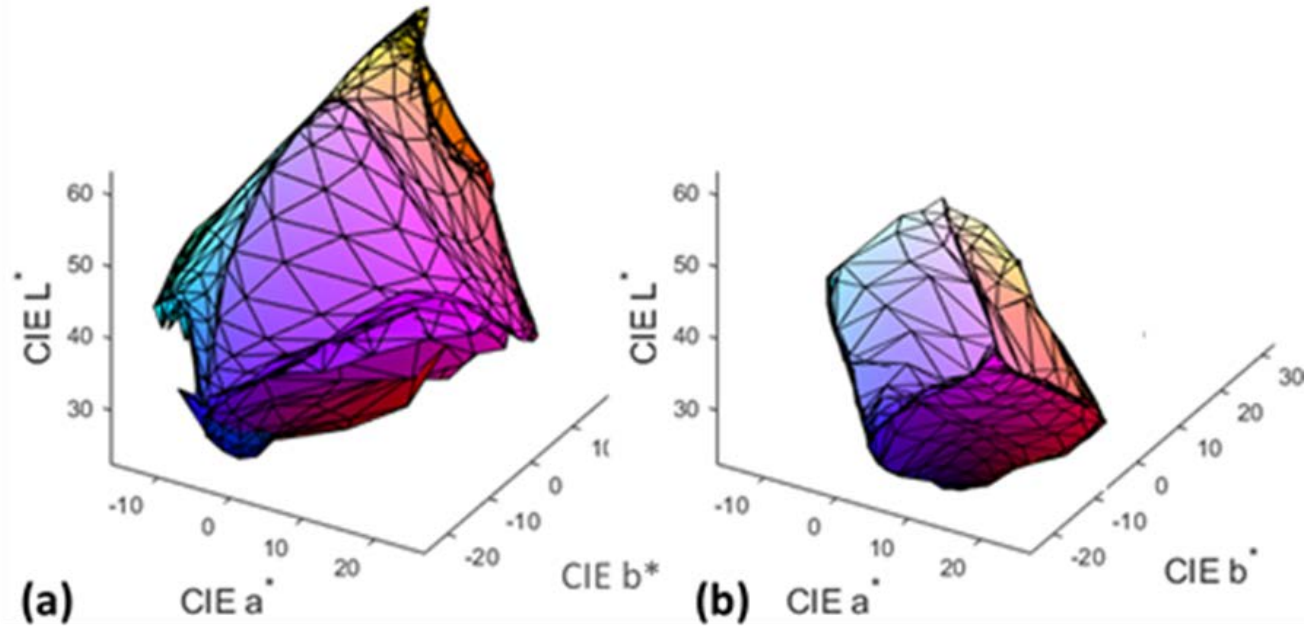


FIGURE 11.2. Example 3D gamut envelopes of two electrophoretic color displays, (a) with four pigments (white and cyan, magenta, yellow) vs. (b) color filter array with red, green, and blue subpixels.

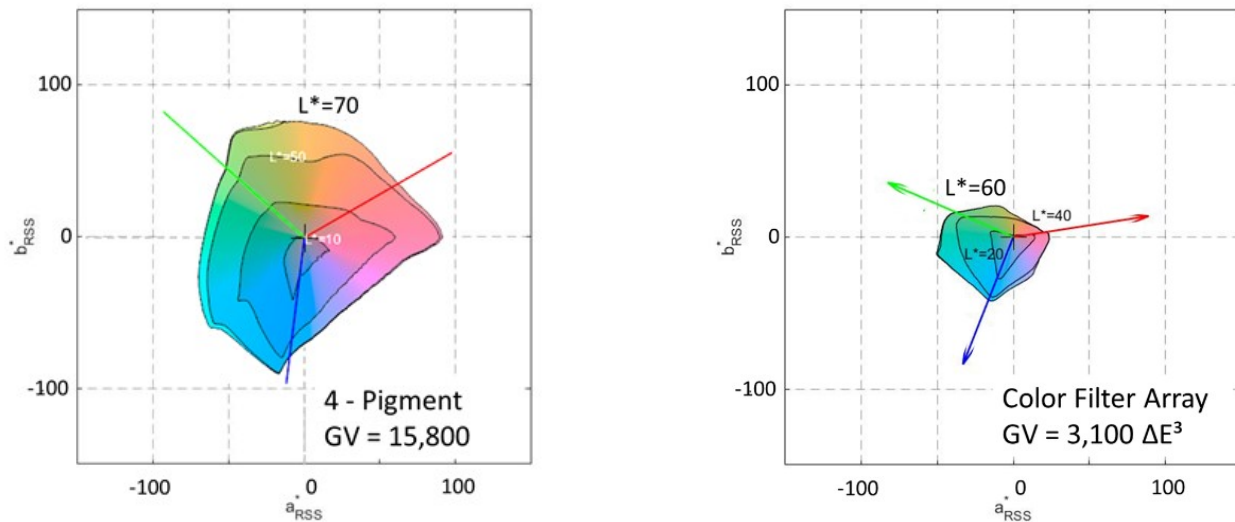


FIGURE 11.3. Example of Gamut Ring diagrams for two electrophoretic color displays, (left) with four pigments (white and cyan, magenta, yellow) vs. (right) color filter array with red, green, and blue subpixels.



The example Gamut Rings diagrams in FIGURE 11.3 are better suited for gamut envelope comparisons because they visualize the incremental contributions to volume for each L^* interval and hue angle. The area enclosed within the outer boundary of each Gamut Rings diagram represents the total color gamut volume. The diagrams illustrate characteristic differences in color capability between the two technologies. It is obvious when comparing the scales for the a_{RSS}^* and b_{RSS}^* axes that the 4-pigment display has much larger overall volumes than the one with color filter array. The 4-pigment technology can produce lighter whites than the one with color filter array because the CMY color pigments can be hidden behind the white for the former, but the light-absorbing RGB color filters are always present for the latter. The distributions of volume increments vs. hue angle at each L^* slice reflect the different color mechanisms: CMY color pigments vs. RGB color filters. For example, each has its own capability to produce yellow, a color that is most saturated at its highest lightness. The 4-pigment display can produce light yellow hues; its only significant contribution to the lightest ($60 \leq L^* \leq 70$) colors come from yellow. For the color filter array, the most significant contribution to yellow comes at lower lightness levels ($40 \leq L^* \leq 60$), showing the incapability to produce yellow at the required high lightness by combining red and green subpixels turned on with blue subpixels turned off.



11.11 CHARACTER-STROKE CONTRAST UNDER AMBIENT ILLUMINATION

ALIAS: Ambient Character-Stroke Contrast

DESCRIPTION: Measure the contrast ratio of a display character strokes under uniform diffuse ambient illumination conditions. The measurement takes into account veiling glare contributions that often corrupt the result. This method assumes an opaque (non-transparent) display.

Units: none, and **Symbol:** CCA.

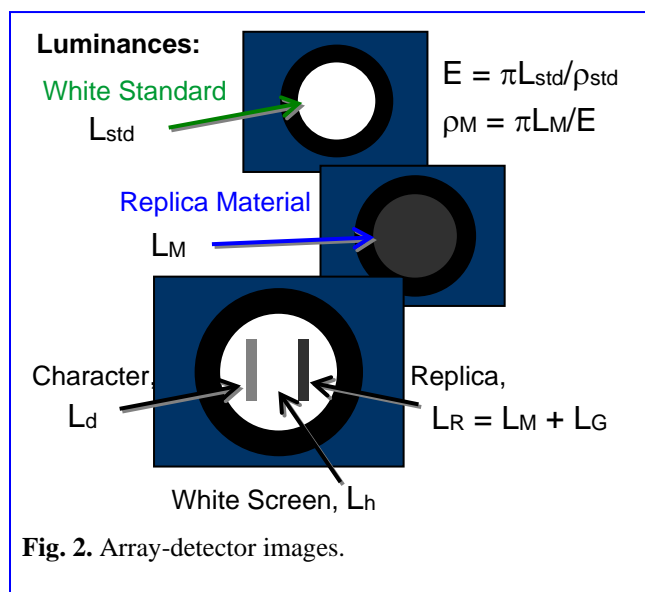
SETUP: As defined by these icons,



standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS:

1. Generally an array detector with a long lens for high magnification is used (10 to 20 camera pixels to each display pixel is preferred), although a luminance meter with a very small measurement field angle could be used. See Fig. 1.
2. Configure an integrating sphere or sampling sphere with a white reference of known reflectance ρ_{std} . Place a capital “T” on the screen to the left of center.
3. Place a replica mask of black-matte material the same size as the character “T” to the right of center as shown.
4. Place a piece of the black-matte material at the right of the screen. The measurement port, size of black-material sample, and detector distance should be configured so that when measuring the black-material reflectance we only see the black material without any bright interior surface corrupting the measurement—see Fig. 2.



PROCEDURE: In making the following measurements, be sure to avoid measuring close to or within the vignette of the measurement port—see Figs. 3 and 4. Refer to Fig. 2:

1. Measure the luminance L_{std} of the white standard.
2. Measure the luminance L_M of the replica material.
3. Measure the luminance L_d of the character “T”.
4. Measure the luminance L_h of the white area next to the character “T”.

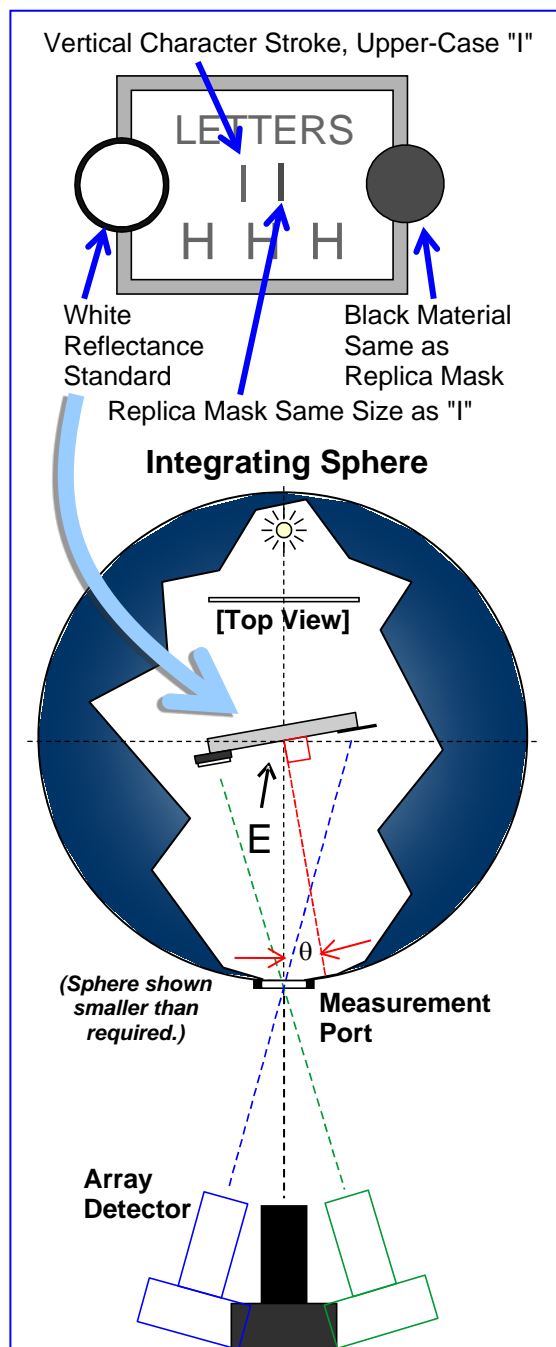


Fig. 1. Uniform diffuse ambient illumination to make small-area luminance or character-contrast measurements with an array detector.



5. Measure the luminance L_R of the replica.

If this is a purely reflective display, proceed to Analysis below. If this is an emissive display, then we need to make darkroom measurements of its luminances.

Figure 5 shows a thin tapered replica that will also serve as a replica in the above measurement if it should prove hard to cut a replica of the proper size.

6. Refer to Fig. 5. In a darkroom, measure the following luminances: L'_h , L'_d , and L'_R (these will all be zero for purely reflective displays). For the dark measurements, avoid the edges of the dark areas (nearby strong glare from bright regions).

ANALYSIS: (If you are measuring a purely reflective display, then set L'_h , L'_d , and L'_R to be zero in the following otherwise use the values obtained in step 6 above.) The illuminance is given by

$$E = \pi L_{\text{std}} / \rho_{\text{std}} \quad (1)$$

The glare correction is

$$L_G = L_R - L_M. \quad (2)$$

The reflectances of white and black are:

$$\rho_W = \frac{\pi[L_h - L'_h]}{E}, \quad (3)$$

$$\rho_K = \frac{\pi[L_d - L_G - (L'_d - L'_R)]}{E}. \quad (4)$$

For any design illuminance E_0 , the ambient character contrast is:

$$C_{CA} = \frac{L'_h + \rho_W E_0 / \pi}{L'_d + \rho_K E_0 / \pi} \quad (5)$$

REPORTING: Report C_{CA} and E_0 to no more than three significant figures.

COMMENTS: The subtraction of the glare, L_G and L'_R , from white, L_h and L'_h , respectively, that we might be tempted to make in Eq. (3) may be too much of a correction because these replica luminances depend upon the size of the replica, which should not affect the white value. If an estimation can be obtained for the large-area veiling glares L''_G and L''_R , perhaps by using a black area outside the measurement area, then the white reflectance can be corrected:

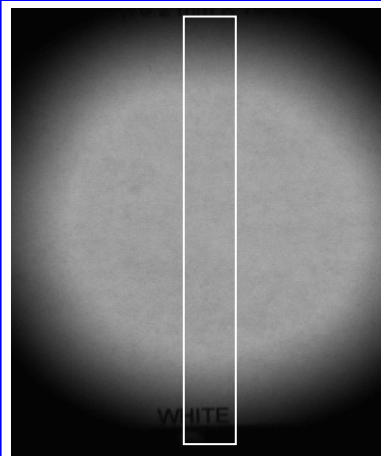


Fig. 3. Vignette from measurement port.

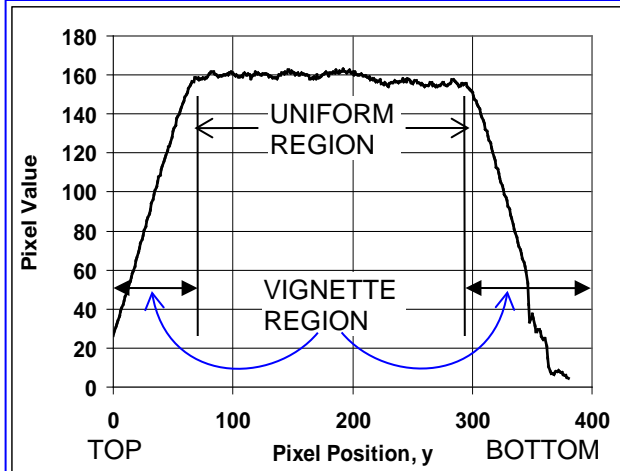


Fig. 4. Uniform region within vignette.

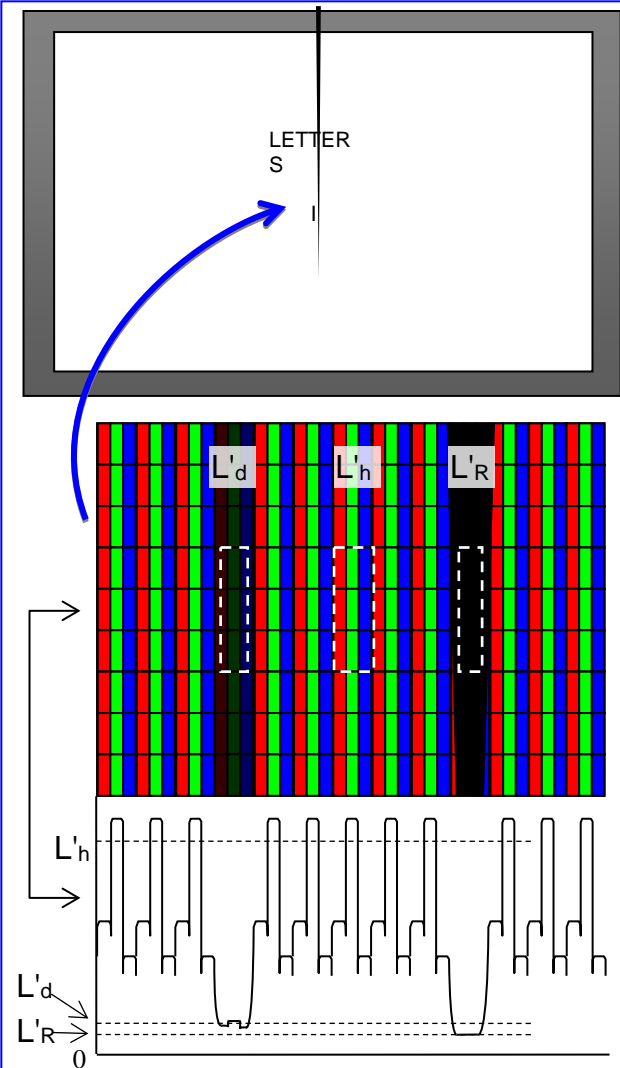


Fig. 5. Narrow-taper replica mask usage in darkroom.



$$\rho_W = \frac{\pi[L_h - L''_G - (L'_h - L''_R)]}{E} \quad (6)$$

Please note: All the above corrections for glare [Eqs. (1)-(6)] become more important as the contrast of the display increases. They are approximations that will provide much better contrast values than if we made no attempt to correct for veiling glare in the detector.

11.12 DIAGNOSTIC: CHARACTERIZING HEMISPHERE UNIFORMITY

Illuminance uniformity of an integrating sphere or hemisphere is important when measuring hemispherical diffuse reflectance factor of the display. The illuminance on the display and the diffuse white reflectance standard should be as close as possible in order to achieve the correct reflectance factor. One way to evaluate the illuminance distribution inside the integrating sphere or hemisphere is to measure the luminance distribution of its interior wall. If the wall is Lambertian and its luminance is uniform, the illuminance inside the sphere or hemisphere should be uniform regardless of position. Therefore, the relative deviation of luminance over the interior hemisphere that the display sees can be used as a diagnostic to evaluate how good the integrating sphere or hemisphere is. One potential method to measure luminance distribution of the interior wall is to use mirror-like sphere or hemisphere as a means to view the interior wall.

A polished sphere or hemisphere is placed where the center of the display is to be located. A simple digital camera can photograph the sphere and examine the reflected luminance of the wall in the virtual image of the polished hemisphere. For example, using a polished stainless-steel ladle from a department store, one can cut off the handle and mount it near the center of the integrating sphere. Figure 1 shows the image of the ladle and the horizontal and vertical cross-sections of the ladle image. The round ring in the ladle image is the crack between the two hemispheres of the large integrating sphere. Because of the table within the sphere, there is a non-uniform darkening of the interior wall luminance as one moves down along the wall toward the table structure. The gross darkening at the bottom in the vertical profile is the kinematic mount for the samples and the hemisphere holder directly beneath the polished hemisphere (see inset). The horizontal luminance uniformity appears to be good. The relative standard deviation of the pixel counts within the two dips can be used as a uniformity of the luminance distribution.

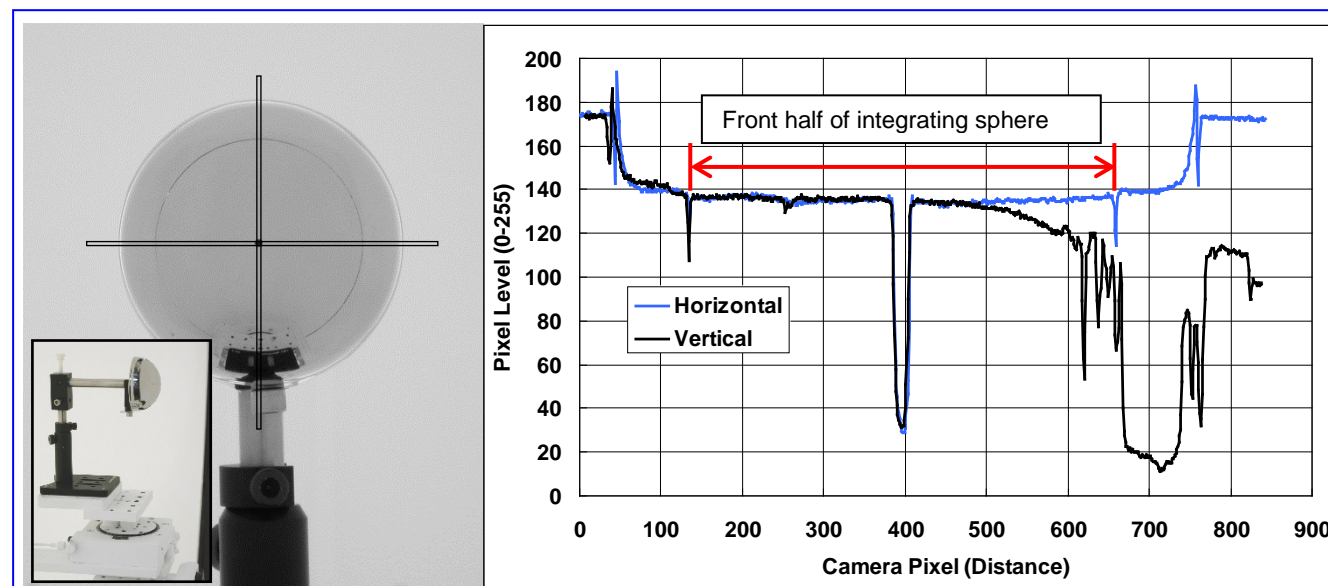


Fig. 1. Ladle scoop mounted near the center of the integrating sphere (inset) with the camera image of the ladle indicating the interior structure and wall luminance of the sphere. The narrow rectangles indicate the measured region shown in the graph at the right.

To check the specular reflectance of the polished hemisphere, one can use a uniform source with a large exit port placed at a distance away. For example, a uniform source with a 150 mm exit port is placed at 1 m away in Figure 2. The inset shows the polished hemisphere rotated approximately 20° clockwise with the source at 45° from the hemisphere axis. The data are taken with a 16-bit array camera (CCD, charge-coupled-device) that exhibits an approximate 1 % uncertainty in its measurements of the small areas in the reflection of the source. The data in Figure 2 shows that approximately a 1 % to 2 % relative measurement of the luminance of the source can be made from 0° to 90°—the luminance distribution in front of



the polished hemisphere. It is interesting that the polished hemisphere allows one to measure well behind the plane of the hemisphere and obtaining almost the entire luminance distribution surrounding it, although rather distorted. This little device allows one to quickly spot any large luminance non-uniformity along the inside wall of any integrating sphere or other type of hemispherical illuminator. By way of illustration, Figure 3 shows how the uniformity of the front hemisphere of the integrating sphere changes as a square black card is placed behind the polished hemisphere. When the size of the edge of the square card reaches approximately 15 cm and increases thereafter a darkening is observed on the front hemisphere that increases with the square size. This verifies the rule-of-thumb that objects need to be approximately less than 1/7 (13 cm for the 91 cm sphere) the diameter of the integrating sphere in order to not adversely affect the uniformity. Because the reflectance of the polished surface is not uniform, the small-square data appears somewhat raised in the middle. A more refined use of the polished hemisphere would account for this specular non-uniformity as well as any flat-field correction with the array camera.

REFLECTION

REFLECTION

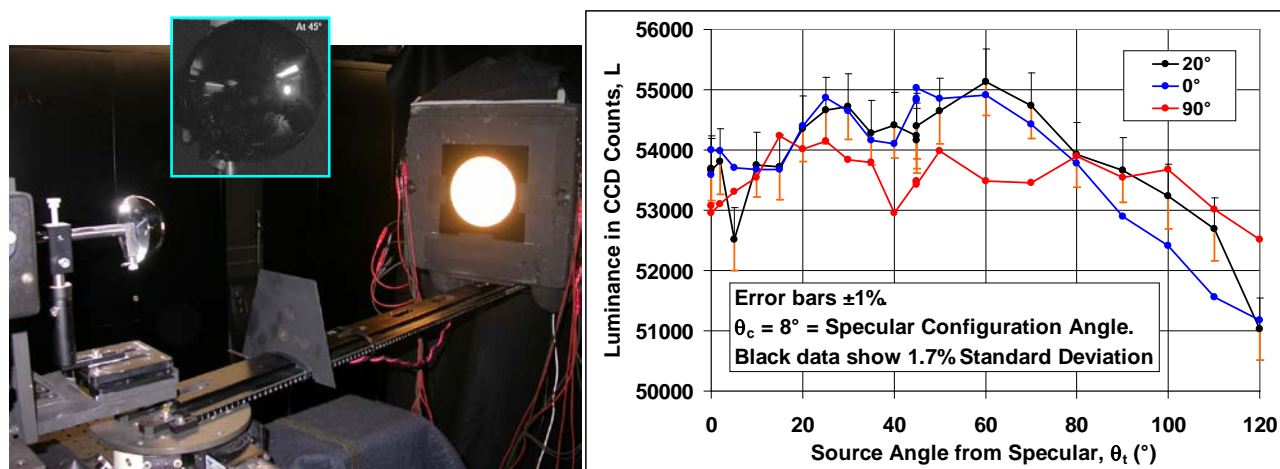


Fig. 2. Measurement of the specular reflectance of the polished hemisphere (soup ladle) for the array camera at a specular configuration angle θ_c of $\theta_0 = \theta_c = 8^\circ$. The inset shows the image of the source at the source angle of 45° (with room lights on in order to see the ladle). The graph shows the measurement results for three orientations of the polished hemisphere rotated about the axis of symmetry of the hemisphere. The inset shows a 20° clockwise rotation of the polished hemisphere.

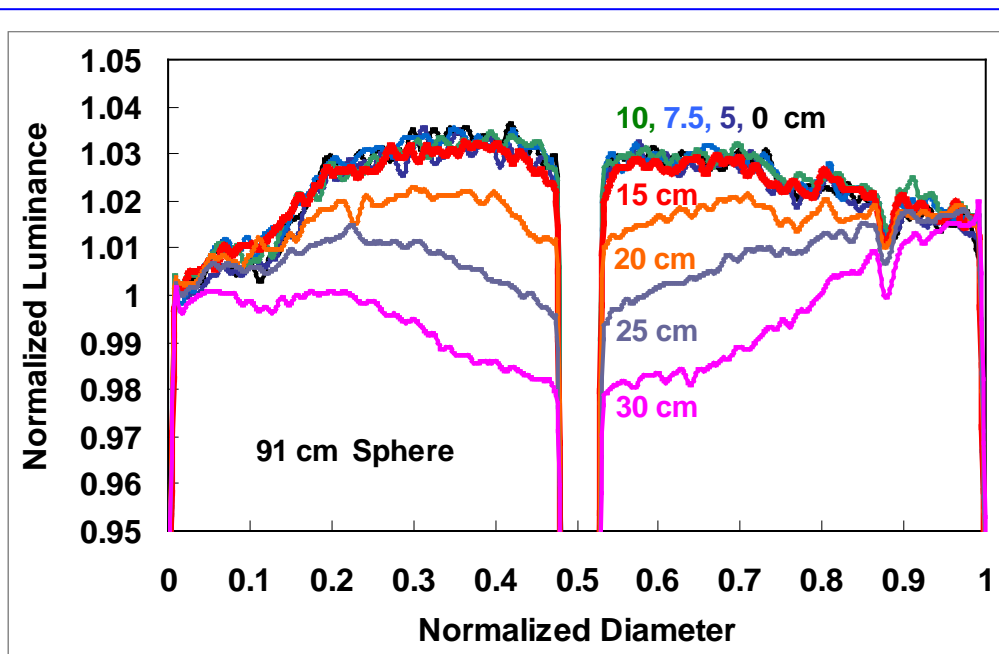


Fig. 3. Change in uniformity of the front of the hemisphere of the 91 cm diameter integrating sphere as a function of the size of a square black card behind the polished hemisphere.



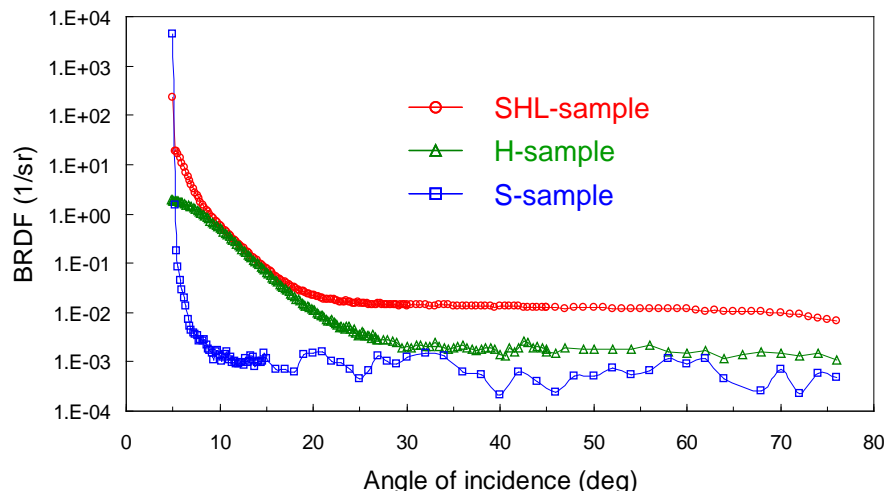
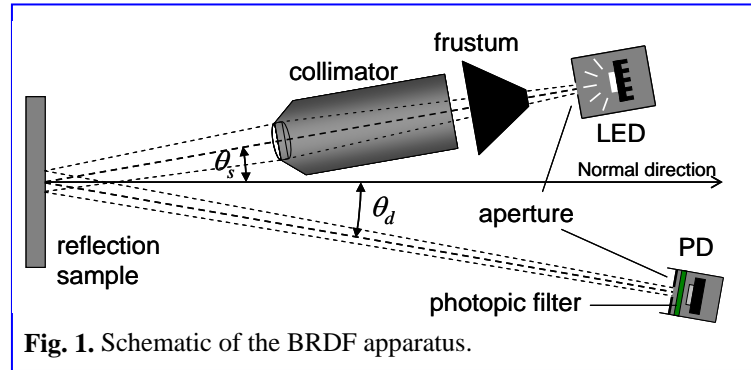
11.13 DIAGNOSTIC: VALIDATION OF BRDF SYSTEM

Bidirectional reflectance distribution function (BRDF) measurement provides a great deal of information about a display's reflection properties. In principle, one can determine the reflectance of an arbitrary display device for any type of illumination source-detector geometry if we have its BRDF data. However, the great utility of the BRDF data is tempered by the difficulty of the measurement. Inter-comparisons between different BRDF systems are often difficult due to differences in detector signatures and the sensitivities to the measurement configurations. Given this difficulty, a correlation to a direct reflection measurement at a specific source and detector geometry is proposed to validate the system. Among various methods used to characterize display reflection, the hemispherical diffuse reflectance measurement performed with an integrating sphere can be the most appropriate choice owing to its highest robustness and reproducibility.

As a practical example, one can construct a high-resolution in-plane BRDF measurement apparatus using an array-type light emitting diode (LED) as a light source, a photodiode (PD) with a photopic filter (V_λ filter) as a detector, and two rotation stages, one for the sample and the other for the light source. Figure 1 shows a schematic of the apparatus. Light from the LED is passed through a circular aperture with a certain diameter, e.g. 1 mm. A long-focal-length lens is used to focus the light onto a detector aperture with an appropriate diameter, e.g. 5 mm after being reflected by a test sample. The diameter of the specular image of the source aperture is made to be slightly less than the detector aperture. A frustum can be located between the collimating lens and the LED source in order to prevent unwanted stray light from entering the collimator, and the entire source apparatus is wrapped with black felt to reduce stray light around the room. The measurement results are acquired in a darkroom where all the surfaces nearby the apparatus are painted black or covered with black felt. The angular resolution is determined by the distance between the center of the reflection sample and the detector aperture. For example, if the distance is 150 cm, the angular resolution is 0.19° with 5 mm diameter of the detector aperture. Photocurrent from the PD is proportional to the luminous flux of the reflected beam entering the detector aperture. In order to determine the amount of incident luminous flux on the reflection sample, a reference black glass is placed at the sample position and the corresponding photocurrent J measured with source and detector both placed in a specular reflection configuration where source angle θ_s and detector angle θ_d are equal. The luminous flux from the LED source can be monitored by an additional PD located inside the collimator and near the lens. Any level change in the monitor PD photocurrent permits corrections to be made in the incident luminous flux during the BRDF measurements.

BRDF is defined by the ratio of the luminance from the sample to the illuminance on the sample. Since it is a ratio, it can be expressed by the photocurrents as:

$$B(\theta_s) = \frac{L_v}{E_v} = \frac{\zeta_b J_s}{J_b \Omega_d \cos \theta_d}, \quad (1)$$





where B is the BRDF in sr^{-1} , L_v is the luminance from the sample, E_v is the illuminance on the sample, ζ_b is the specular reflectance of the reference black glass, J_b is the photocurrent proportional to the luminance from the reference black glass, J_s is the photocurrent proportional to the luminance from the sample, Ω_d is the solid angle from the sample center to the detector aperture, θ_s is the source angle, and θ_d is the angle of the detector from the sample normal as shown in Figure 1. It is interesting to note that BRDF is not explicitly dependent upon θ_s . Its dependence upon θ_s comes through J_s . For the measurements, the detector angle θ_d can be set to 5° , and the source angle θ_s is changed while taking measurements of the photocurrent J_s . Moving the source keeping the detector fixed is ideally the same as moving the detector and keeping the source fixed. Keeping the source fixed and moving the detector has advantages in that the illuminated area stays the same size and larger angles from the normal can be explored by the detector. Often a 6° specular configuration angle is used for initial alignment, but larger angles may be needed if the physical constraints of the source and detector demand it.

Figure 2 shows typical examples of BRDF profiles for three different types of reflection samples. The sample designated as S is an ordinary black glass with a dominant specular reflection. The sample designated as H has dominant haze component. The sample designated as SHL has specular, haze and Lambertian components simultaneously. When the reference black glass is replaced by the test sample, a slight angular readjustment may be required to make the specularly reflected beam point through the detector aperture.

For sample H, it is difficult to find the specular direction due to the absence of a distinct specular reflection. Hence, special care should be taken in placing sample H so as not to change the angle at which the photocurrent of the reference black glass is measured. Sample S has the strongest peak in the specular direction and a relatively flat Lambertian-like scatter. The fluctuations in the BRDF appearing after 13° are due to a low signal-to-noise ratio. The other two samples show rather stable BRDF profiles over all incidence angles because of the large amount of diffuse scatter compared to sample S. The diffuse scatter manifested by sample S is likely caused by imperfections in the sample (microscopic scratches and digs) as well as scattering within the source.

Assuming that the sample is located at the center of the sphere and that the wall luminance of the sphere is uniform, the hemispherical diffuse reflectance factor is given by:

$$R = \frac{\pi L}{E} = \zeta_s + 2\pi \int_0^{\pi/2} B_d(\theta) \sin \theta \cos \theta d\theta, \quad (2)$$

where ζ_s is the specular reflectance of the sample and $B_d(\theta)$ is the diffuse component of the BRDF without the specular component. The measured BRDF at 5° (specular direction) is then used as $B_d(\theta = 0)$ and so are the BRDF data at the angle θ_s , as $B_d(\theta = \theta_s - 5^\circ)$. After zero is assigned to the BRDF at 90° , BRDF data at every 0.1° or 0.2° can be generated by a suitable interpolation method, e.g. spline-interpolation method. Then numerical integration can be done using the BRDF data.

Table 1 summarizes the calculated results and includes the values of the hemispherical diffuse reflectance factors of the samples, which are measured directly by the use of integrating spheres.

Table 1. Hemispherical diffuse reflectance factors calculated by BRDF data and measured with integrating sphere.

Samples	BRDF			Integrating sphere	Deviation (%)
	Specular	Diffuse	Total		
S	0.0400	0.0023	0.0423	0.0422	0.42 %
H	0.0000	0.0485	0.0485	0.0479	1.2 %
SHL	0.0018	0.1132	0.1151	0.1154	-0.28 %

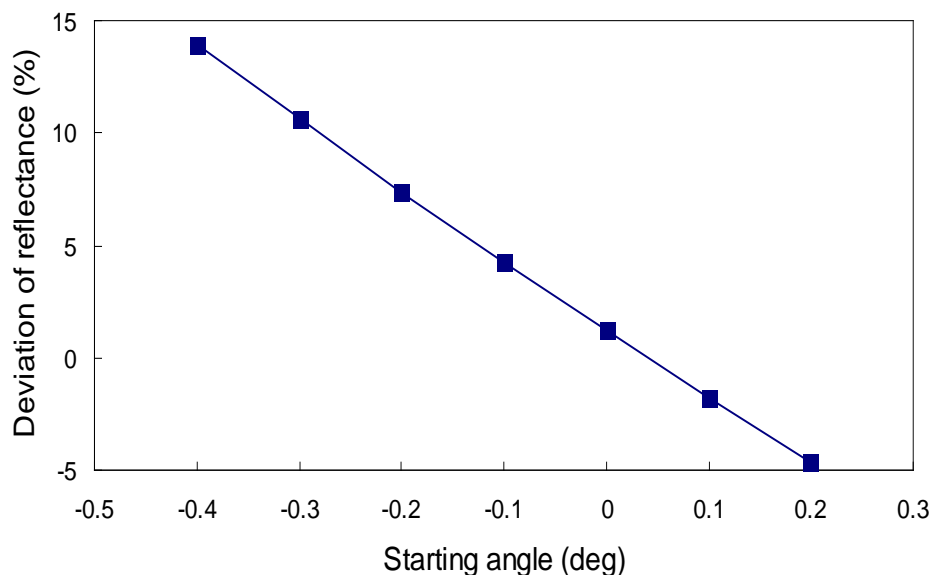


Fig. 3. Deviation of calculated reflectance factor from the measured value for sample H as a function of starting angle.



The agreement between the calculated and measured values is quite excellent considering that the relative uncertainty at the 95 % confidence level is estimated to be 1 % for the direct integrating-sphere method. In addition to the uncertainty of the hemispherical diffuse reflectance factor measured with the integrating spheres, the difference between the calculated and the measured values can be produced by the angular misalignment of the BRDF apparatus, error in numerical integration, photopic response differences in detectors used with the integrating-sphere apparatus and BRDF apparatus. The light source spectral difference can also affect the results, but the effect should be negligible because the samples are spectrally flat.

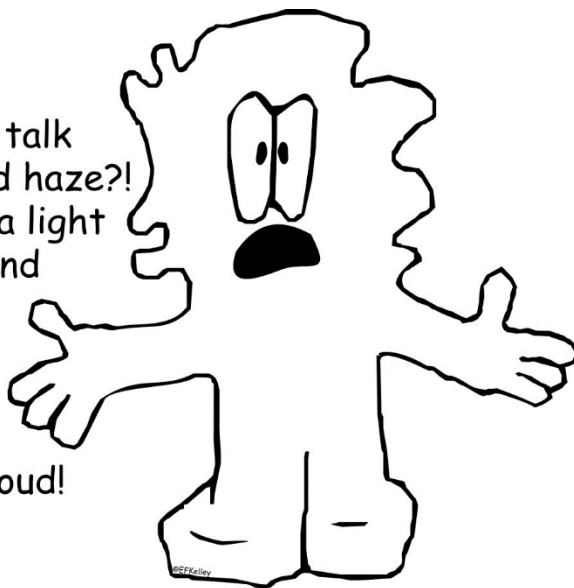
The results in Table 1 clearly show that the deviation of the calculated value from the directly measured value is less than ± 0.5 % for samples S and SHL, while the sample H produces a deviation of more than 1 %. The reason for the relatively large deviation for sample H can be explained by the fact that there is no specular image at the detector aperture, and thus a slight angular misalignment may happen during replacement from the reference black glass to sample H. The angular misalignment can be readjusted for the other two samples because they produced specular images. One can estimate the effect of angular misalignment for the sample H by measuring BRDF after changing the starting angle. The results demonstrate that an angular misalignment of 0.1° can bring about a change of 3 % in calculated reflectance factor, as shown in Figure 3. Consequently, accurate sample alignment is critical when measuring BRDF for reflection samples without specular reflection.

Error can also be introduced by the numerical integration rule. Four different numerical integration rules can be tried: Trapezoidal, Simpson's, Simpson's 3/8, and Bode's. For the samples H and SHL, the deviation between maximum and minimum reflectance factor for these samples are less than 0.2 %, whereas it is as large as 0.8 % for sample S. In Figure 2, the BRDF profile of sample S changes much faster than that for the other two samples as a function of angle and hence the integrated value is more easily affected by different integration rules.

Another factor that can contribute an error in numerical integration is the interpolation of BRDF data between the final angle of measurement and 90° in θ . The worst case is if all values are set to zero in this range and integrate the BRDF data only up to the final angle of measurement. In such a case, the calculated reflectance factors are reduced by 0.25 %, 0.83 %, and 1.3 % for samples S, H, and SHL, respectively. It is obvious from Figure 1 that the reduction is larger for the sample with a higher Lambertian component in BRDF. Therefore, one can expect that the uncertainty caused by selecting different interpolation methods can affect the overall reflectance factor by much less than 0.5 %.

This comparison demonstrates how a robust direct reflection measurement such as hemispherical diffuse reflectance factor can be used as an independent diagnostic to check the BRDF measurement system.

What's all this talk
about BRDF and haze?!
All you need is a light
source at 45° and
you're done!
Why make
everything so
complicated?!!
For cryin' out loud!



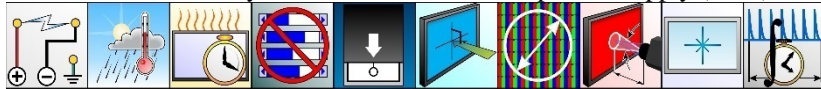
RUSTIC METROLOGY



11.14 TRANSMITTANCE (REGULAR INCLUDED)

DESCRIPTION: Measure an appropriate transmission parameter (transmittance factor, diffuse transmittance, and the spectral counterparts) of a display at near normal to the display that is configured for color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under uniform diffuse illumination provided by an integrating sphere. It is not appropriate to use this method while the display is emitting light. **Units:** none; **Symbol:** $T_{Q,di/0}$, $\tau_{Q,di/0}$, $T(\lambda)_{Q,di/0}$, $\tau(\lambda)_{Q,di/0}$, etc..

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: This method is similar to ASTM D1003^{*} and ISO 13468-1[†]. The integrating sphere configuration shown in Figure (1) is recommended for this transmission measurement. In the simplest configuration, a light source (not shown) illuminates the sphere interior, and there is one port (the sample port) facing the LMD. Another configuration can add a light trap port (opposite the sample port) with a white reflection standard is placed at that port. It is recommended that the integrating sphere have a monitor detector that measures any change in illuminance in the sphere.

Surround: The light source illuminating the sphere should be continuous and have a smooth broadband spectrum, preferably approximating CIE Illuminant D65. The spectral characteristics of the light source shall be kept constant during the measurement. The integrating sphere should have a small port with a diffuser and optical detector with a photopic filter to monitor changes in illuminance in the sphere. The photocurrent J from the monitor detector is proportional to the illuminance in the sphere. The port for the monitor detector shall have baffles to prevent light from the light source or the sample port from falling on the detector directly. The luminous reflectance of the interior sphere surface and baffles shall be more than 90 % and have no more than 3 % reflectance variation over the surfaces.

The integrating sphere may be of any diameter as long as the total port area does not exceed 4.0 % of the internal area of the sphere. It is recommended that the diameter of the integrating sphere is not less than 150 mm so that specimens of a reasonable size can be used. When diameter of the integrating sphere is 150 mm and the diameter of the sample is 30 mm, the ratio of the total port area to the internal area of the sphere is 1.0 %. For regular included measurements, a port plug or diffuse white standard with similar reflectance to the inner wall can be used to fill the light trap port. If placing the display at the sample port significantly changes the spectral distribution of the light in the sphere, adding a compensation port to the sphere (see ISO 13468-1) can help. This is especially true if the sample is a transparent display that changes its reflection characteristics with the rendered color (such as LCDs). However, the sampling sphere method described in the next section should be used for emissive displays that change their transmission characteristics when rendering different colors.

A flat sample shall be held against the sample port so that the normal of the sample is within 2° of the normal of the sample port. The LMD is aligned normal to the center of the sample port at an approximate distance of 0.5 m. The measurement field shall be focused on the sample port plane. The sphere interior should provide uniform illumination on the screen, with the screen receiving a constant luminance over its hemispherical inclination angles. This criterion is often satisfied when the sphere's internal light source dominates the illuminance inside the sphere compared to any sample contribution.

The size of the sample port and detector port should be slightly larger than the entrance pupil of the LMD to avoid vignetting. The display surface should be placed as close as possible to the inner white surface of the sphere at the sample port. If the emitting surface of the display is significantly recessed from the front surface of the display, then the sphere sample port size is important: For a 1 % introduced error the ratio of the diameter D_{sp} of the sample port to the recess depth h should be $D_{sp}/h = 8$; for a 0.1% introduced error, $D_{sp}/h = 16$. Care should be taken to avoid putting excessive pressure on the display surface.

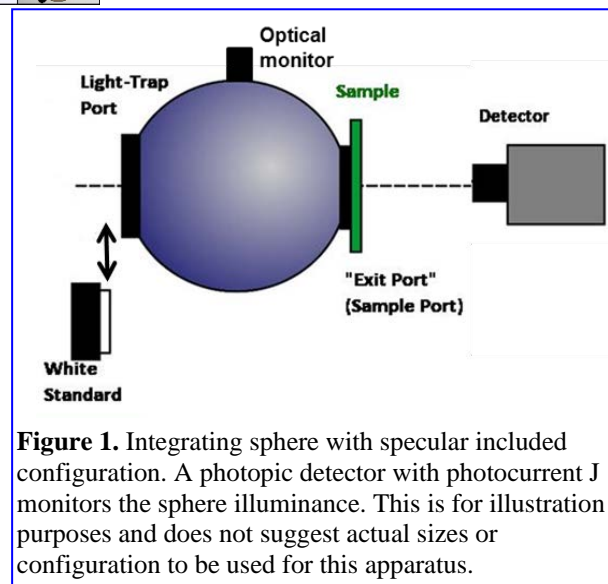


Figure 1. Integrating sphere with specular included configuration. A photopic detector with photocurrent J monitors the sphere illuminance. This is for illustration purposes and does not suggest actual sizes or configuration to be used for this apparatus.

^{*} ASTM D1003-00, *Standard test method for haze and luminous transmittance of transparent plastics*, 2000

[†] ISO 13468-1, *Plastics – Determination of the total luminous transmittance of transparent materials – Part 1: Single-beam instrument*



PROCEDURE: Configure the display to the desired color Q (if transmittance is color dependent) and ensure that the display is not emitting light.

1. If the integrating sphere has a light trap port, place a port plug or white reflectance standard in the plane of the light trap port. The port plug or reflectance standard should have similar reflectance as the interior sphere wall.
2. Place the back of the display surface against the sample port. Turn on the sphere light source and allow it to stabilize.
3. Place the LMD 0.5 m from the display and align the LMD normal to the display surface. The LMD measurement field should be centered about the sample port and focused at the sample port plane.
4. In a dark room, measure the luminance $L_{di/0}$ or spectral radiance $L_{di/0}(\lambda)$ from the display, and record the monitor current $J_{di/0}$.
5. Remove the display from the sample port. Measure the luminance L_s or spectral radiance $L_s(\lambda)$ from the sample port, and record the monitor current J_s .

ANALYSIS: The following analysis defines the photometric values. The spectral values will have similar equations. The luminous transmittance factor $T_{di/0}$ from hemispherical diffuse illumination with specular included is given by:

$$T_{Q,di/0} = \frac{L_{di/0}}{L_s} \frac{J_s}{J_{di/0}}. \quad (1)$$

REPORTING: Report the size of the integrating sphere, size of the sample port, the orientation of the display, the CCT of the sphere light source, all measured luminance and photocurrent values, the color rendered on the display, and the hemispherical diffuse transmittance factor.

COMMENTS: (1) **Other Configurations:** Other configurations can also be used instead of an integrating sphere, such as a sampling sphere or hemisphere. (2) **Uniformity of**

Surround Luminance: It is most important that the sphere wall have a relatively uniform luminance distribution, especially near the sample port. (3) **Detector Self-**

reflection and Stray Light: A frustum or stray-light-elimination tube (see Appendix A2) should be used to in front of the LMD to minimize self-reflection and stray light. The detector can also be moved back from the sample port to minimize LMD self-reflections. (4) **Robustness:** If the display's transmission properties are completely unknown, the hemispherical transmission measurement with specular included is the most general and robust measurement that can be made. (5) **Radiometric Measurements:** For greatest accuracy and flexibility, we recommend that you consider making spectrally resolved measurements and calculating the spectral transmission parameters. (6) **Lamp Light Source:** A broadband light source with a continuous spectral power distribution should be used. If a broadband source approximating D65 is not available, we recommend using a stabilized quartz-tungsten-halogen (QTH) lamp. To avoid heating the interior of the sphere (and the display), it is recommended that the lamp be external to the sphere and its housing fan cooled. Particularly if you are making spectrally resolved measurements, an additional external infrared blocking filter (e.g., KG-3 glass filter) may be used to reduce the infrared radiation entering the sphere as well as reduce the red content of the spectrum.

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Analysis example	
Transmitted display luminance $L_{di/0}$ (cd/m ²)	135
Sphere luminance L_s (cd/m ²)	254
Monitor current with display at port $J_{di/0}$ (mA)	1.31
Monitor current without display at port J_s (mA)	1.23
Calculate $T_{Q,di/0}$	0.416



11.14.1 SAMPLING SPHERE IMPLEMENTATION

DESCRIPTION: Measure an appropriate transmission parameter (transmittance factor, diffuse transmittance, and the spectral counterparts) of a display at near normal to the display that is exhibiting a selected color Q ($Q = W, R, G, B, C, M, Y, K, S, \text{etc.}$) under uniform diffuse illumination provided by a sampling sphere. This method is appropriate if the transmission properties of the display need to be measured while the display is emitting light. **Units:** none; **Symbol:** $T_{Q, \text{di}/0}$, $\tau_{Q, \text{di}/0}$, $T(\lambda)_{Q, \text{di}/0}$, $\tau(\lambda)_{Q, \text{di}/0}$, etc..

ADDITIONAL SETUP: The sampling sphere configuration shown in Figure (1) is recommended for this transmission measurement. The sample port is where the white reflectance standard or display will be placed for measurements. Opposite the sample port, and slightly outside the measurement field of the LMD is the detector port.

Surround: When measuring the sample port, ideally the LMD should only see the white background of the interior wall of the sampling sphere. The detector port should be a few degrees off from the LMD viewing direction. The size of the sample port and detector port should be slightly larger than the entrance pupil of the LMD to avoid vignetting. The display surface should be placed as close as possible to the inner white surface of the sphere at the sample port. If the emitting surface of the display is significantly recessed from the front surface of the display, then the sphere sample port size is important.

Illuminance Measurement: The illuminance (or spectral irradiance) on the display can be determined by measuring the interior sphere wall adjacent to the sample port. The wall reflectance factor ρ_{wall} of that interior wall location can be determined by comparing the luminance L_{wall} (or spectral radiance) of the wall with that of a calibrated white standard placed at the sample port: $\rho_{\text{wall}} = \rho_{\text{std}} L_{\text{wall}} / L_{\text{std}}$, where L_{std} is the luminance measured from the white standard in the plane of the sample port. The same relationship is also used for spectral measurements. The illuminance might also be measured using a photopic photodiode. We will assume a wall luminance measurement here. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

PROCEDURE: Render the desired color Q on the display surface.

1. Place a white reflectance standard of known spectral reflectance or reflectance in the center of the plane of the sample port.
2. Align the LMD so that its measurement field is centered through the detector port of the sphere and focused at the center of the reflectance standard. Allow the sphere lamp to stabilize. Measure the luminance L_{std} or spectral radiance $L_{\text{std}}(\lambda)$ from the reflectance standard.
3. Pivot the LMD a few degrees so that its measurement field is centered through the detector port of the sphere and focused at a position on the interior sphere wall adjacent to the sample port. The LMD measurement field should be completely filled by the light from the interior wall. Ideally the LMD field of view should also be completely filled by light from the interior wall. Measure the luminance L_{wall} or spectral radiance $L_{\text{wall}}(\lambda)$ from the interior wall adjacent to the sample port.
4. Replace the white reflectance standard by a display rendering a color Q , where the back of the display was placed against the sample port. Note the orientation of the display (e.g., landscape or portrait). Measure the interior wall luminance $L_{\text{sph, On}}$ or spectral radiance $L_{\text{sph, On}}(\lambda)$ with the display at the sampling port.
5. Move the LMD to the front of the display and align so that it is normal to the display surface, is focused on the sample port, and its measurement field is centered on the sample port. Measure the transmitted luminance $L_{Q, T}$ or spectral radiance $L_{Q, T}(\lambda)$ at the center of the sample port.
6. If the display is emitting light, then additional measurements are needed. In this case, the light emission $L_{Q, \text{em}}$ from the display should also be measured with the sphere light turned off.
7. With the sphere light turned off, move the LMD behind the sphere, align the measurement field of the LMD through the center of the detector port, and focused on the same interior wall position next to the sample port. Measure the luminance $L_{\text{sph, Off}}$ or spectral radiance $L_{\text{sph, Off}}(\lambda)$ with the sphere light off and the display at the sampling port rendering a color Q . For non-emissive displays, these values will be zero.

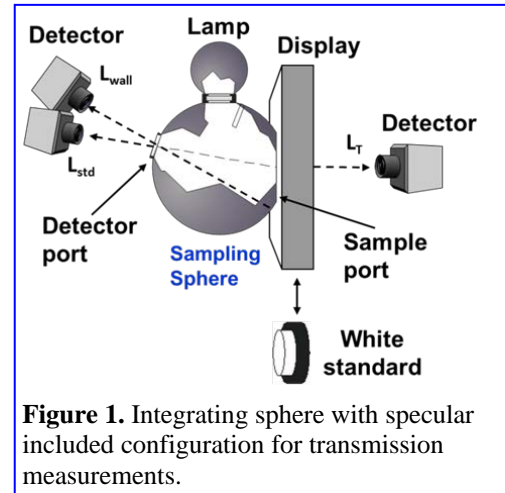


Figure 1. Integrating sphere with specular included configuration for transmission measurements.



ANALYSIS: The following analysis defines the photometric values. The spectral values will have similar equations. The reflectance R_{wall} of the interior sphere wall is given by:

$$R_{wall} = \rho_{std} \frac{L_{wall}}{L_{std}}. \quad (1)$$

The illuminance $E_{Q,T}$ on the back of the display rendering a color Q at the sample port, with the sphere lamp on, is given by:

$$E_{Q,T} = \pi \frac{L_{sph,On}}{R_{wall}}. \quad (2)$$

The illuminance $E_{Q,off}$ on the back of the display rendering a color Q at the sample port, with the sphere lamp off, is given by:

$$E_{Q,off} = \pi \frac{L_{sph,Off}}{R_{wall}}. \quad (3)$$

The diffuse hemispherical transmittance with regular included of the display rendering a color Q is given by:

$$T_{Q,di/0} = \pi \frac{[L_{Q,T} - L_{Q,em}]}{[E_{Q,T} - E_{Q,Off}]}. \quad (4)$$

For non-emissive displays $L_{Q,em}$ and $E_{Q,Off}$ will be zero.

REPORTING: Report the size of the integrating sphere, size of the sample and detector port, inclination angle θ_d of the detector port, the orientation of the display, the CCT of the sphere light source, and the calculated wall reflectance, all measured luminance values, the color rendered on the display, and the hemispherical diffuse transmittance.

COMMENTS: (1) **Measurement Port Diameter:** The detector port diameter should be 20 % to 30 % larger than the diameter of the detector lens—the entrance pupil of the detector and the measurement field should be smaller than the detector port diameter.

(2) **Radiometric Measurements:** For greatest accuracy and flexibility, we recommend that you consider making spectrally resolved measurements and calculating the spectral transmission parameters. This is especially true when measuring the transmission properties of emitting displays. (3) **Lamp Light Source:** If transmission measurements are performed on emissive displays,

the lamp flux needs to be sufficiently high such that the transmitted light signal is easily measurably over that from the display emission.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example

Luminance of standard at sample port L_{std} (cd/m ²)	1670
Luminance of wall with standard at port L_{wall} (cd/m ²)	1642
Reflectance of standard ρ_{std}	0.99
Luminance of wall with display at port and surround on $L_{sph,On}$ (cd/m ²)	1474
Luminance of wall with display at port and surround off $L_{sph,Off}$ (cd/m ²)	43.1
Calculate $E_{Q,T}$ (lux)	4757
Calculate $E_{Q,off}$ (lux)	139
Front luminance of display at port and surround on $L_{Q,T}$ (cd/m ²)	402.4
Front luminance of display at port and surround on $L_{Q,em}$ (cd/m ²)	205
Calculate $T_{Q,di/0}$	0.134

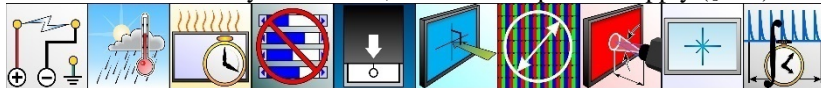


11.15 TRANSMITTANCE (REGULAR EXCLUDED)

CAUTION: This measurement can be strongly affected by the LMD measurement field, the scatter properties of the display, and the size of the port used to exclude the regular component especially if nontrivial matrix scatter or haze is present. Take care to ensure that the display is oriented properly, i.e., that the display normal bisects the angle between the sample port and the specular port.

DESCRIPTION: Measure the transmission parameter (transmittance factor, diffuse transmittance, and the spectral counterparts) of a display at near normal to the display that is configured for color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under uniform diffuse illumination with regular component excluded provided by an integrating sphere. It is not appropriate to use this method while the display is emitting light. This method assumes that the transmission properties of the display are not affected by the illumination level on the display. **Units:** none; **Symbol:** $T_{Q,de/0}$, $\tau_{Q,de/0}$, $T(\lambda)_{Q,de/0}$, $\tau(\lambda)_{Q,de/0}$, etc..

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: This method is similar to the spectrophotometer version of ASTM D1003*. The integrating sphere configuration shown in Figure (1) is used for this regular excluded transmission measurement. It is recommended that the integrating sphere have a monitor detector that measures any change in illuminance in the sphere.

Surround: The light source illuminating the sphere should be continuous and have a smooth broadband spectrum, preferably approximating CIE Illuminant D65. The spectral characteristics of the light source shall be kept constant during the measurement. The integrating sphere should have a small port with a diffuser and optical detector with a photopic filter to monitor changes in illuminance in the sphere. The photocurrent J from the monitor detector is proportional to the illuminance in the sphere. The port for the monitor detector shall have baffles to prevent light from the light source or the sample port from falling on the detector directly. The luminous reflectance of the interior sphere surface and baffles shall be more than 90 % and have no more than 3 % reflectance variation over the surfaces.

The total port area of the integrating sphere should not exceed 4,0 % of the internal area of the sphere. It is recommended that the diameter of the integrating sphere is not less than 150 mm so that specimens of a reasonable size can be used. When the diameter of the integrating sphere is 150 mm and the diameters of the sample, light trap ports are 30 mm, the ratio of the total port area to the internal area of the sphere is 2,0 %. The monitor detector shall be used to compensate for change in the sphere illuminance due to the presence of the display at the sample port.

A detailed illustration of the regular excluded and transmitted haze geometry is given in Figure 2. The sample port and light trap port shall be centered on the same optical axis as the LMD.

The diameter of the sphere z_s , and the light trap port diameter d_{LT} shall be sized such that the opening of the light trap port shall subtend $\theta_{LT}=8^\circ$ from the center of the sample port. The LMD shall be positioned a distance z_{LMD} away from the sphere, producing a measurement field of diameter d_{mf} focused at the sample port, where $d_{mf} = z_d d_{pmf} / (z_{LMD} + z_s)$ and d_{pmf} is the projected measurement field diameter at the light trap port. The

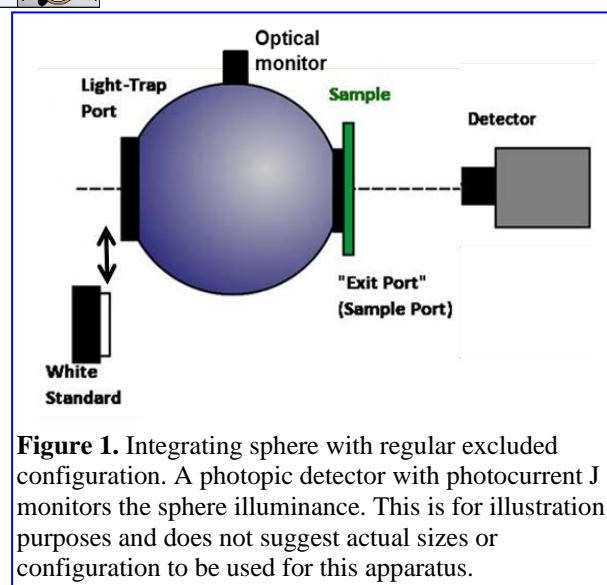


Figure 1. Integrating sphere with regular excluded configuration. A photopic detector with photocurrent J monitors the sphere illuminance. This is for illustration purposes and does not suggest actual sizes or configuration to be used for this apparatus.

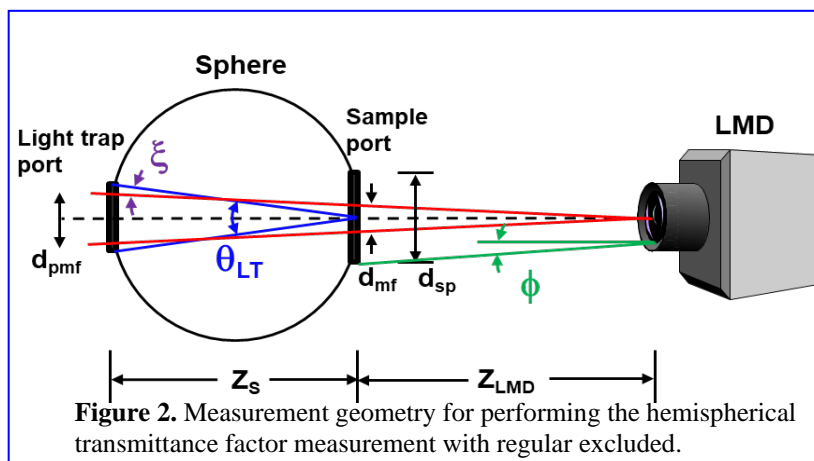


Figure 2. Measurement geometry for performing the hemispherical transmittance factor measurement with regular excluded.

* ASTM D1003-00, *Standard test method for haze and luminous transmittance of transparent plastics*, 2000



LMD and sphere shall be set up such that the angular gap (annulus) $\xi = \theta_{LT}/2 - \arctan[d_{pmf}/(2 z_s)]$ between the projected measurement field diameter d_{pmf} and the light trap port diameter shall give $\xi = 1.3^\circ$. When the above requirements are satisfied, the maximum angle ϕ that any measured light ray can have relative to the normal is less than 3° . Ensure that the LMD measurement field is contained within the image of the light trap port area.

Illuminance Measurement: The illuminance (or spectral irradiance) on the display can be determined by measuring the interior sphere wall adjacent to the sample port. The wall reflectance factor ρ_{wall} of that interior wall location can be determined by comparing the luminance L_{wall} (or spectral radiance) of the wall with that of a calibrated white standard placed at the sample port: $\rho_{wall} = \rho_{std} L_{wall} / L_{std}$, where L_{std} is the luminance measured from the white standard in the plane of the sample port. The same relationship is also used for spectral measurements. The illuminance might also be measured using a photopic photodiode. We will assume a wall luminance measurement here. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

PROCEDURE (PHOTOMETRIC):

1. Place a port plug or diffuse white standard at the light trap port. Turn on the integrating sphere light source and allow the light source and LMD to stabilize. The measurement configuration in Fig. 2 shall be set up in a dark room, and no external light should enter into the integrating sphere.
2. Align the LMD normal to the sample port and focus the measurement field at the center of the port. Measure the luminance L_s at the center of the sample port, and record the monitor detector photocurrent value J_s .
3. Render the desired color on the display and place the back of the display against the opening of the sphere sample port at the desired orientation relative to the detector. Measure the transmitted luminance $L_{di/0}$ through the display at the center of the sample port, and record the monitor detector value $J_{di/0}$.
4. Remove the white reflection standard or port plug at the light trap port. Measure the transmitted luminance $L_{de/0}$ through the display with the regular component excluded and record the photocurrent value $J_{de/0}$ of the monitor detector.
5. Remove the display from the sample port. Measure the background luminance L_{bg} with the sample port and light trap ports open, and record the photocurrent value J_{bg} of the monitor detector.



ANALYSIS: The following analysis defines the photometric values. The spectral values will have similar equations. The measurement provides a transmittance factor for hemispherical illumination with regular includes, similar to § 11.1.3 Transmittance (Regular included):

$$T_{Q,di/0} = \frac{L_{di/0}}{L_s} \frac{J_s}{J_{di/0}}. \quad (1)$$

The hemispherical transmittance factor with regular excluded is given by:

$$T_{Q,de/0} = \frac{J_s}{L_s} \left[\frac{L_{de/0}}{J_{de/0}} - \frac{L_{bg} L_{di/0} J_s}{L_s J_{bg} J_{di/0}} \right]. \quad (2)$$

The percent haze in transmission can be expressed as:

$$H_{Q,de/0} = 100\% \times \frac{T_{Q,de/0}}{T_{Q,di/0}}. \quad (3)$$

REPORTING: Report the size of the integrating sphere, size of the light port and sample port, the orientation of the display, the CCT of the sphere light source, all measured luminance and photocurrent values, the color rendered on the display, and the hemispherical transmittance factor with included and excluded, and the percent haze in transmission.

COMMENTS: None.

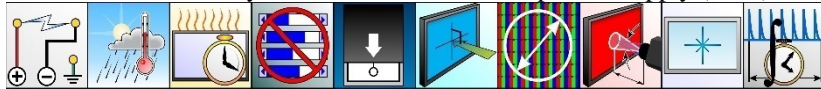
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example	
Transmitted display luminance with port plug $L_{di/0}$ (cd/m ²)	851.9
Sphere luminance without display with port plug L_s (cd/m ²)	1656
Monitor current with display at sample port with port plug $J_{di/0}$ (mA)	8.14
Monitor current without display at sample port with port plug J_s (mA)	8.1
Transmitted luminance of display without port plug $L_{de/0}$ (cd/m ²)	85.83
Monitor current with display at sample port without port plug $J_{de/0}$ (mA)	7.17
Sphere luminance without display without port plug L_{bg} (cd/m ²)	0.4695
Monitor current without display at sample port with port plug J_{bg} (mA)	7.14
Calculate $T_{Q,di/0}$	0.512
Calculate $T_{Q,de/0}$	0.0584
Calculate $H_{Q,de/0}$	11.4%



11.16 RING-LIGHT TRANSMISSION

DESCRIPTION: We measure the directed transmittance factor or spectral directed transmittance factor of a display at near normal to the display that is configured for color Q ($Q = W, R, G, B, C, M, Y, K, S$, etc.) under ring-light illumination. The luminous ring-light directed transmittance factor can be calculated from the spectral measurement or determined directly by a photometric measurement. **Units:** none; and **Symbol:** $T_{Q,45/0}$, $T(\lambda)_{Q,45/0}$.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Ring-light illumination should provide uniform directed illumination on the display over all azimuthal angles at a given inclination angle $\theta_{b,dir}$. It should also provide a uniform illumination over the measurement field of the LMD. The ring-light emitting surface should be parallel to the display surface and symmetric about the display's center of screen. The distance between the ring-light and display surface should be adjusted to obtain an inclination angle $\theta_{b,dir} > 30^\circ$, with a ring subtense of $< 0.5^\circ$. It is recommended to use an inclination angle of $\theta_{b,dir} = 45^\circ$. The design working distance of the ring-light should approximately correspond to the

$\theta_{b,dir} = 45^\circ$ inclination angle. The LMD is aligned to view the center of the display and normal to the surface. The LMD is focused on the display surface. The optical axis of the LMD should be centered within the ring-light's clear aperture. The use of small ring-lights should be avoided. It is suggested that the distance of the ring-light from the display should be much greater than the thickness of the display's optical layers—see Fig. 2 in section § 11.5.

Illuminance Measurement: It is recommended that the illuminance $E_{b,dir}$ be determined via either a cosine-corrected illuminance meter or a calibrated white reflectance standard of known luminance factor $\beta_{std-ring}$ for this given illumination geometry; that is, the white standard must be calibrated for this geometry. When making a measurement with the illuminance meter or white standard or target, it should replace the display and be positioned in the same measurement plane as the display. Refer to § 11.1.3 Source Measurements and Characterization for tips on making illuminance measurements.

Lamps: Quartz-tungsten-halogen lamps stabilized to less than $\pm 1\%$ per hour from a fiber-optic illuminator are often used as lamps. Most fiber-optic illuminators employ IR absorbing filters that reduce the red output providing a slightly greenish illumination. If measurements are performed on emissive displays, the ring-light illuminance needs to be sufficiently high such that the transmitted light luminance is significantly larger than the display luminance. White LEDs and xenon sources are finding applications for such fiber-optic illuminators.

PROCEDURE:

1. Place a white reflectance standard at the sample plane used for the display measurements. Place the ring-light facing the reflectance standard, centered on the optical axis, and positioned at a distance such that its light is incident at a 45° inclination angle to the optic axis. Position the LMD behind the ring-light, approximately 0.5 m from the sample plane, and align the optical axis of the LMD centered and normal to the reflectance standard surface.
2. Allow the ring-light illumination to stabilize. Measure the luminance L_{std} or spectral radiance $L_{std}(\lambda)$ of the light reflected from the reflectance standard.
3. Replace the reflectance standard with the back of the display positioned at the same sample plane. The desired measurement location on the display shall be centered about the measurement field of the LMD
4. Move the LMD to the front of the display, maintaining the same measurement distance, and align the LMD to the same optical axis and measurement field position as in the last measurement. A test pattern may be used to position the measurement field to the same location.

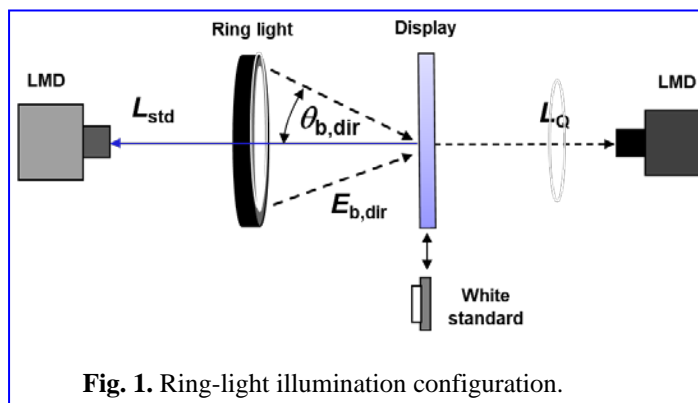


Fig. 1. Ring-light illumination configuration.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example	
Directed reflectance factor of standard at 45/0 $\beta_{std-ring0}$	0.995
Luminance from white standard with ring-light at 45/0 L_{std} (cd/m ²)	2413
Calculate ring-light illuminance on back of display $E_{b,dir}$ (lux)	7619
Darkroom luminance of transparent display rendering white color $L_{Q,45/0}$ (cd/m ²)	0
Transmitted luminance of transparent display rendering white color $L_{Q,45/0}$ (cd/m ²)	1.42
Calculate $T_{Q45/0}$.00059



5. With the display rendering the desired color Q , measure the luminance $L_{Q,45/0}$ or spectral radiance $L_{Q,45/0}(\lambda)$ of the transmitted light through the display.
6. Measure the luminance L_Q at the center of the display color pattern with the ring light OFF (this can be accomplished by disconnecting the fiber optic cable from the lamp source or shuttering the lamp).

ANALYSIS: The ring-light illuminance $E_{b,dir}$ on the back of display is determined by:

$$E_{b,dir} = \frac{\pi L_{std}}{\beta_{std-ring}} \quad (1)$$

The luminous directed transmittance factor for the 45° back illumination/normal detection configuration is given by.:

$$T_{Q,45/0} = \frac{\pi(L_{Q,45/0} - L_Q)}{E_{b,dir}} \quad (2)$$

Similar equations can be used for spectral measurements.

REPORTING: Report the measurement geometry, the calculated illuminance $E_{b,dir}$ on the back of the display, the CCT of the ring-light illumination, the luminance values $L_{Q,45/0}$ and L_Q and the luminous directed transmittance factor for the 45° back illumination/normal detection configuration.

COMMENTS: None.



12. MOTION-ARTIFACT MEASUREMENTS

Modern electronic displays are often used to show dynamic imagery, such as video and animated graphics. In general, they do this by displaying a sequence of static images, called frames. The goal of a dynamic display is usually to render dynamic imagery with an apparent spatial resolution, color fidelity, and smoothness of motion that rivals the appearance of moving objects in the real world. This chapter is not confined to any particular display technology.

Success in meeting this goal depends to a large extent on the temporal properties of the display: what is the frame rate, and how rapidly can a display element switch from one gray level or color to another, and is backlight modulation present? The frame rate is the time analog of spatial resolution, and the switching time is the analog of the shape and size of a spatial pixel.

In this chapter we describe measurements of the basic motion-rendering properties of the display. Because of its importance in contemporary displays, we devote considerable space to metrics of motion blur. Motion blur arises when the eye tracks a moving image, while the display presents individual frames that persist for significant fractions of a frame duration, or longer. As a result, the image is smeared across the retina during the frame duration. Motion blur is usually measured in terms of the blur of a moving edge, and we provide several methods for measuring and quantifying moving-edge blur. Motion blur can also be measured in terms of the reduction in contrast of a moving line or grating, and we provide metrics for those techniques as well.

In addition to blur, color distortions can occur in the vicinity of a moving edge when the several color primaries of a display do not exhibit identical motion blur, or if the blur in each color depends upon the magnitude of the transition. A metric is proposed to calculate the amount of color distortion on a moving edge.

Color breakup (CBU) is another important type of motion artifact. It arises in field-sequential color (FSC) displays which produce a single-color frame by showing a rapid sequence of several primary color fields (often red, green, and blue) and relying on the human eye to blend the fields into the trichromatic mixture color. Color breakup occurs when the eye executes fast motions (saccades) so that successive fields are not spatially registered. The amount of color breakup will depend upon the rate of color fields, and on the number and selection of primaries, and on the content within each field. CBU metrics attempt to provide relevant standard measures of this phenomenon.

Dynamic false contours (DFC) are related to the temporal distribution of the light within a frame period. Some display technologies generate, within a frame period, several short light pulses with a predefined duration, called weighted sub-frames, where the light intensity is controlled by activating one or more sub-frames. Typically, the order of the sub-frames within a frame period is fixed and their activation depends on the content. For moving (chromatic) objects, temporal integration of the light on the retina occurs along the motion trajectory. Depending on the content, the motion speed, and the sub-frame distribution, new colors may appear as false contours. A metric is proposed that attempts to quantify this phenomenon.

Because an entire frame may not be presented at once (for example it may be scanned from top to bottom), geometric distortions may be manifest in moving imagery. Another sort of artifact, called wireframe flicker, is produced as a result of spatial and temporal aliasing in the rendition of narrow moving lines. We provide metrics for these artifacts as well.

Some problems in the display of moving imagery may be the result of signal processing prior to the display panel itself. While these are different in character, they are common in modern integrated displays and so we address them here if useful measurements can be defined. Examples are judder, frame-tearing, repeated frames and dropped frames.

Related to this chapter are some tutorial considerations in the appendix. These sections will assist in calculating the gray levels and shades needed as well as understanding judder and blur from moving patterns. Here are the pertinent sections: § A26 Perceptively Equal Gray-Shade Intervals, § A27 Blur, Judder, & Smooth-Pursuit Eye Tracking, § A9 Array Camera Considerations. For clarity, we provide here a brief summary of notation used in this chapter. Where possible, we have tried to be consistent with the rest of the document:

f	time as measured in display frames	T	frame period in seconds ($= 1/w$), also Δt
t	time in seconds	R	relative luminance
Δt	time between samples in seconds	M	number of graylevels used as start or end of edge transition
v	edge speed in pixels/frame	$C_{\text{start}}, C_{\text{end}}$	start and end colors of an edge
p	horizontal position in display pixels	$V_{\text{start}}, V_{\text{end}}$	start and end graylevels of an edge
x	horizontal position in degrees of visual angle	r	display visual resolution in px/degree
Δx	distance between samples in degree of visual angle (§ 12.4.3)	τ	time interval between samples, in frames
c	horizontal position in camera pixels	$S(f)$	Temporal step response as a function of time expressed in frames
m	camera magnification (camera pixels/display pixels)	$R(f)$	Moving-edge temporal profile, f in frames
w	display frame rate in Hz or frames/s	$R(p)$	Moving-edge spatial profile, p are display pixels
w_x	spatial frequency in cycles/deg		



In future editions of this chapter we will attempt to include additional metrics. Here is a list of possible candidates and metrics that are under development:

1. DIRECTIONALLY VARIANT JUDDER

This is the motion-dependent temporal instability of a moving pattern. Rather than smooth motion, there may be hesitations, inconsistencies, or other interruptions of smooth motion of the moving content.

2. LINE BREAKUP

Some display under certain circumstances can produce a visual strobing effect for saccadic eye movement or external motion interferences as may be observed by a moving hand with fingers extended.

3. MOVING-LINE CONTRAST DEGRADATION & SPREADING

This is the contrast degradation by the spreading of a line of one gray level moving horizontally from left to right across a background of a different gray level assuming smooth-eye-pursuit tracking of the line — also called line spreading. We compare a static line (with the same levels) with this moving line to determine a contrast degradation of the line relative to the background. When the line goes into motion, the contrast of the static line is spread over distance. The line width is a single pixel. (However, other line widths may be additionally employed if agreed to by all interested parties.) NOTE: The speed of the line must be 1 px/frame or more, preferable 4 px/frame minimum. If the speed is slower, we migrate toward the case of wireframe flickering (see § 12.6.). See number 7 below, Dynamic Contrast of Moving Patterns for an image-based determination of the degradation of the moving line.

4. GRAY-SCALE ABERRATIONS

This pertains to motion artifacts that occur within the moving-edge blur region, assuming smooth-pursuit eye tracking of a moving pattern.

Blur may be thought of as a smooth transition between one level of gray of a simple pattern and another level of gray composing the background. However, there can be perturbations on this smooth transition within the blur region that produce brightening or darkening which may result from overshoot, undershoot, ripple, or other artifacts. This metric is based upon luminance measurements which can resolve blur-region perturbations distinguished from smooth blurring.

5. DYNAMIC FALSE CONTOUR GENERATION

This are distortions associated with an object in motion that geometrically differ from the object at rest besides blur and other artifacts already covered in this chapter.

This metric is distinguished from blur and other metrics introduced in this section. It refers to characteristics which can be generated and are visible independent of the human visual system, such as banding, elongation of corners, indentations, flaring, visibility of new sub-geometric structures, and rounding.

6. INVERSION EDGE ARTIFACTS

This is an artifact of motion which can occur on pixel boundaries on certain moving patterns due to bit enhancement techniques such as spatial or temporal dithering.

7. DYNAMIC CONTRAST OF MOVING PATTERNS

This is the dynamic contrast of moving patterns assuming smooth-pursuit eye tracking. Several types of patterns can be used.

The dynamic contrast of a moving image is based upon its static form. Generally, we are dealing with only a small area of the screen. Suppose we have a rectangular-shaped static image of horizontal width N_x and vertical height N_y . Let the relative location of the pixels associated with the static image be n_h and n_v in the (x, y) direction respectively for $h = 1, 2, \dots, N_x$ and $v = 1, 2, \dots, N_y$, and let the luminance of a pixel at location (h, v) be S_{hv} for the static image. Consider moving that pattern at a speed u (in px/s) [if u is a velocity, then there it will be defined by (u_x, u_y)]. Assuming smooth-pursuit eye tracking where the moving image is precisely identified properly by the same relative coordinates (n_h, n_v) , let the luminance associated with each pixel in the moving image be M_{hv} (this process amounts to registering the moving image with the static image). The dynamic contrast (based upon the definition of Michelson contrast) of the moving image is:

$$C_d = \frac{1}{N_x N_y} \sum_{h=1}^{N_x} \sum_{v=1}^{N_y} \left(1 - \frac{|M_{hv} - S_{hv}|}{M_{hv} + S_{hv}} \right).$$

A number of patterns or images will be considered including a 100 px moving box and a single-pixel moving line of one gray level on a background of another gray level. The dynamic contrast ranges from zero to one—a perfect moving image exactly like the static image has a dynamic contrast of one. This lends itself to also expressing the dynamic contrast in percent by multiplying C_d by 100%.

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



12.1 MOVING-EDGE-BLUR INTRODUCTION

Many modern display technologies are subject to motion blur. Motion blur arises when the eye tracks a moving image, while the display presents individual frames that persist for significant fractions of a frame duration, or longer. As a result, the image is smeared across the retina during the frame duration. Although motion blur may be manifest in any moving image, one widely used test pattern is a moving edge. This pattern gives rise to measurements of what is called moving-edge blur. In this section we describe methods to measure, and to analyze or quantify moving-edge blur. We begin with a general introduction that describes the basic test patterns and measurement principles. This introduction is followed by a more formal but still general procedure for complete measurement and analysis of moving edge blur. That in turn is followed by a set of specific measurement and analysis techniques.

Test Pattern: Although variants will be discussed below (subsection: Test Pattern Variations), the standard test pattern for moving-edge blur is a vertical edge separating two regions with gray levels V_{start} and V_{end} . The pattern is scrolled horizontally at a speed of v in px/frame (an integer). The direction of travel is such that gray level at the edge changes from V_{start} to V_{end} as time progresses. In the case pictured in Fig. 1, the edge moves from left to right. In practice, the edge can move in either direction, but V_{start} is always defined as the starting gray level and, V_{end} the ending gray level. On the right in Fig. 1 we show an illustration of the possible appearance of the test pattern to a human observer. The edge appears blurred. In the following we explain and quantify this blur.

Origin and Nature of Moving-Edge Blur: Although motion blur manifests itself as a spatial artifact (blur), it is ultimately a consequence of the temporal behavior of the display. For that reason, we first consider the temporal step response (TSR) of the display. This function describes the relative luminance of the display following a change in gray level (the temporal step response is discussed in more detail elsewhere in this document, see § 10.2.2 Response Time). In Fig. 2, we show an example of a step response for a change from gray level $V_{\text{start}} = 0$ to $V_{\text{end}} = 255$ for a particular LCD display. In this case, the change in relative luminance spans more than one frame. As we will see, this step response and the hold-time of the display together determine the amount of motion blur.

In the analysis of motion blur, the absolute luminance values are usually not important; what matters is how the luminance changes over space and time. For this reason, we use the term “relative luminance” to mean a quantity that is proportional to luminance. Unless otherwise noted, the measurements in this section are presumed to operate on relative luminance.

Now we consider a specific case of an edge traveling at a speed of 2 px/frame. If we consider this moving image, we first note that nothing is changing in the vertical direction, so we can restrict our attention to one horizontal line of pixels and a sequence of frames. Fig. 3 shows the distribution of relative luminance along that line of pixels, over the course of nine frames of time, in the neighborhood of the edge. If we examine a single pixel over time, from the bottom of the figure to the top, we see that it starts dark, and at some time transitions gradually to bright. In fact, the shape of the transition is exactly the one shown in Fig. 2.

Although Fig. 3 shows that the motion of the edge is discrete, and occurs in jumps of two pixels each frame, to the human eye this motion will appear smooth (if the pixels are small enough and the frames brief enough). If a human observer tracks the apparent motion of the edge with their eye, they will follow this smooth course. The red line in the figure represents the path followed by a smoothly moving eye that is tracking the apparent motion of the edge.

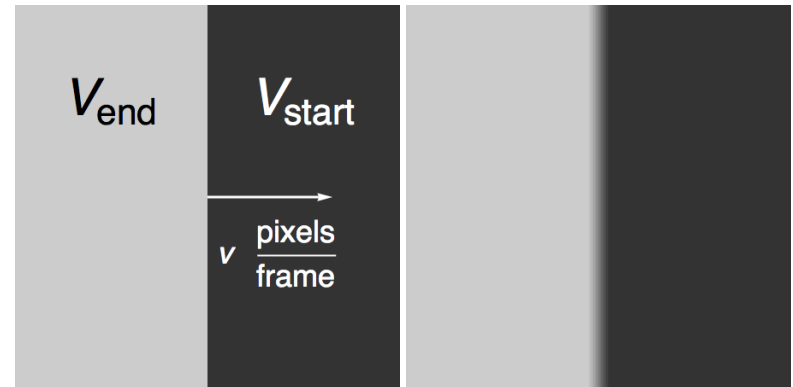


Fig. 1. Moving edge blur test pattern (left) and possible visual appearance when the eye tracks the moving edge (right).

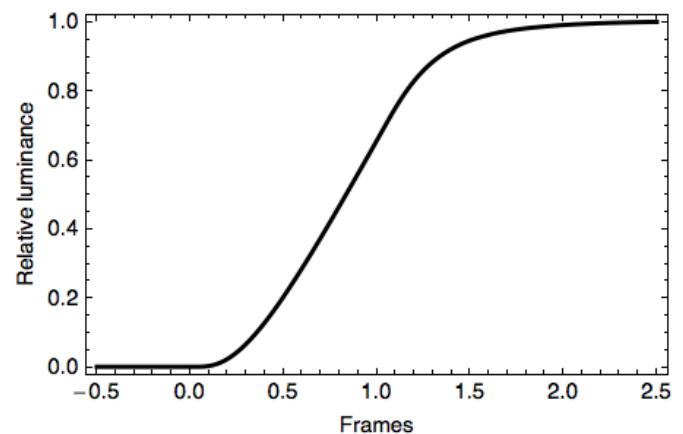


Fig. 2. Temporal step response (TSR) for a particular LCD display.



Knowing the path of the eye, we can transform the coordinates of Fig. 3, to render a picture of the distribution of relative luminance on the retina, rather than on the screen. To do this, we convert from screen coordinate p (px) to retinal pixel coordinate p_r by the formula

$$p_r = p - vf,$$

where f is time in frames and v is speed in px/frame. The result of this transformation is shown in Figure 4.

Now if we consider the relative luminance at any fixed horizontal retinal position (a fixed horizontal coordinate in Fig. 4) we see that it fluctuates with a period of one frame. This is because the eye is moving smoothly while the edge is moving in a saltatory (step by step) fashion. However, if the frame duration is sufficiently short, this fluctuation over time will be invisible to the human eye, and we will see only the luminance averaged over each frame. The result of that averaging is shown in Fig. 5. This is called the moving-edge spatial profile (MESP). This, then, is a picture of the cross-section of the apparent blurred edge seen by the human eye, as illustrated in the right side of Fig. 1.

The preceding example used an edge speed of 2 px/frame. If the exercise is repeated with a different speed, it will be observed that the blur is the same but scaled horizontally in proportion to the speed.

Consequently, it is useful to derive a measure of moving-edge blur that is independent of speed, by dividing the pixel coordinate by the speed in px/frame to obtain a coordinate in frames. The result of this coordinate transform called the moving-edge temporal profile (METP), and it is shown in Fig. 5. Conveniently, it can be shown mathematically that the moving-edge temporal profile (METP) can be obtained directly as the convolution of a pulse, of width equal to the hold time (typically, one frame), and the temporal step response (TSR, as shown in Fig. 2). These two functions are also shown in Fig. 6.

Analyzing the Moving-Edge Temporal Profile (METP): The METP is a useful measure of moving-edge blur, but it is a waveform represented by a large list of numbers. In many contexts we would like a single number metric to characterize the severity of the blur. To a first approximation, this severity is reflected in the width of the blur. Thus most of the analyses of the METP, and the numerical metrics derived from it, are essentially measures of the width of the METP. Several examples are described in detail below. Here we illustrate in general terms one of the simplest

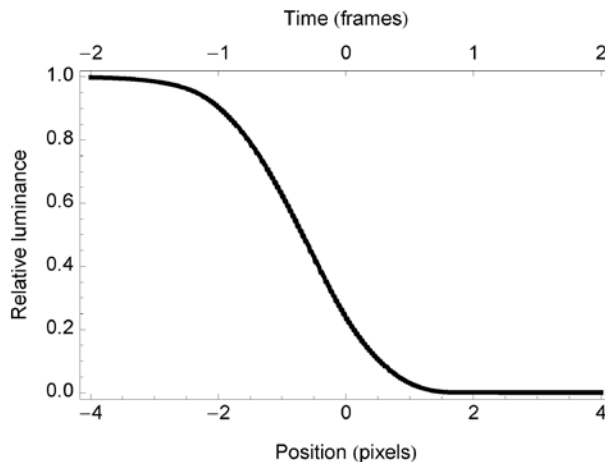


Figure 5. Moving-edge spatial profile (MESP) for a particular LCD display and edge speed (2 px/frame). The moving edge temporal profile is shown by the same curve, but referred to the upper horizontal axis.

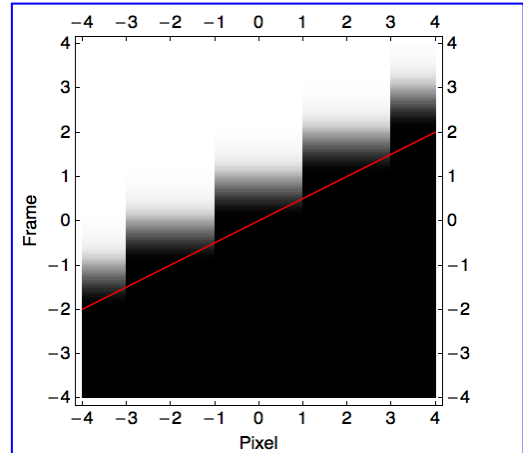


Figure 3. Image depicting relative luminance in the neighborhood of the moving edge as a function of horizontal position and time.

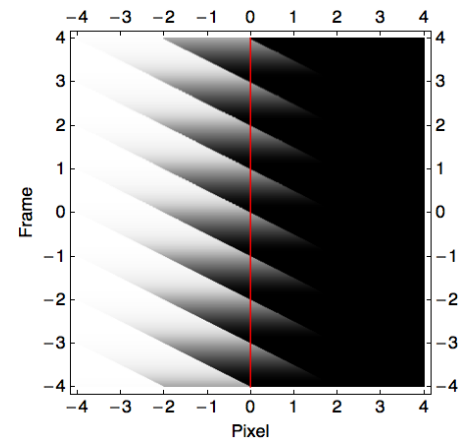


Figure 4. Image depicting relative luminance in the neighborhood of the moving edge as a function of horizontal retinal position and time.

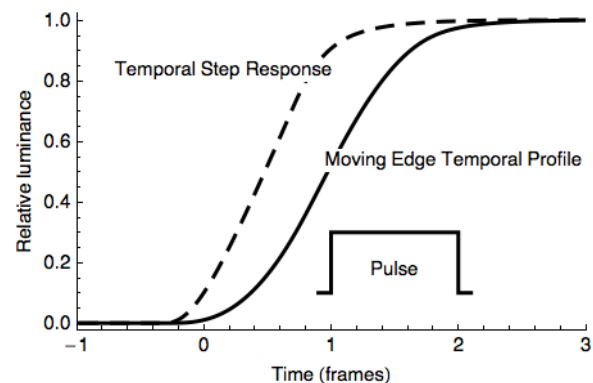


Figure 6. Moving-edge temporal profile (METP). It is the convolution of the temporal step response (TSR) and the pulse of duration one frame.



measures. This consists in locating the minimum and maximum of the METP, and from them identifying the 10 % and 90 % points of the curve. The time interval between those points, in frames, is designated blurred-edge time in frames (BETF), as shown in Fig. 7. This is usually converted to the blurred-edge time (BET) and quantified in milliseconds.

As discussed below, the blurred-edge time (BET) is but one of several metrics that can be derived from the METP. Others include the Gaussian edge time (GET), which is a more robust method of estimating blur width by fitting a Gaussian, and perceived blurred-edge time (PBET), which filters the edge by a human visual contrast-sensitivity function (CSF). Still other metrics are discussed below in following sections.

JND Analysis: A limitation of all of the analysis methods discussed above is that they do not attempt to express their results in units that correspond to the perceptual magnitude of the artifact, or what are often called JND (just-noticeable differences) units. Perceived blurred-edge time (PBET) does incorporate a human visual CSF, but still reports its results in milliseconds rather than JND. To compute JND, what is required is a model of visual sensitivity to spatial patterns. This model must include both the spatial contrast sensitivity function, filtering of the edge image, masking of the blur artifact by the edge itself, and integration over the spatial extent of the edge. One metric described below incorporates this form of analysis.

Multiple Gray levels: Because the transition speed of the display may depend upon the particular pair of gray levels used, it is common to use a set of M gray levels. The measurement and analysis is then repeated for each of the $M(1 - M)$ possible pairings of gray levels. This will yield an equivalent number of metric values. An illustration of this result is shown in Fig. 8. Often these multiple metric values will be combined, for example by averaging, to yield a single metric.

Test Pattern Variations: Many different test patterns may be used. For example, a bar of gray level V_{end} can be used on a background of gray level V_{start} (Fig. 9, left). This enables measurement of two gray level transitions with one test pattern.

However, care must be taken to ensure that the bar is wide enough that the two transitions do not overlap. Further, the bar need not extend the full height of the display; instead, a box can be used (Fig. 9, right), so long as the measurement includes only the region within the lower and upper borders of the box. The box has the virtue of placing less of a load on the display, which may be important for some technologies. Clever engineering can be done to include multiple edges between different gray levels in a single test pattern to expedite the measurement. In general many variations are possible, so long as in the subsequent analysis it is possible to extract the individual moving-edge temporal profile (METP) for distinct V_{start} to V_{end} transitions.

Moving Color Edge Blur: If the several color primaries of a display exhibited identical motion blur, and if that blur did not depend upon the magnitude of the transition, then when an edge between two colors (C_{start} and C_{end}) moved, there would be blur, but no color distortion. Instead of a sharp transition between two colors there would be a gradual transition along a straight line in chromaticity space. All colors on the screen would be linear combinations of the two colors C_{start} and C_{end} .

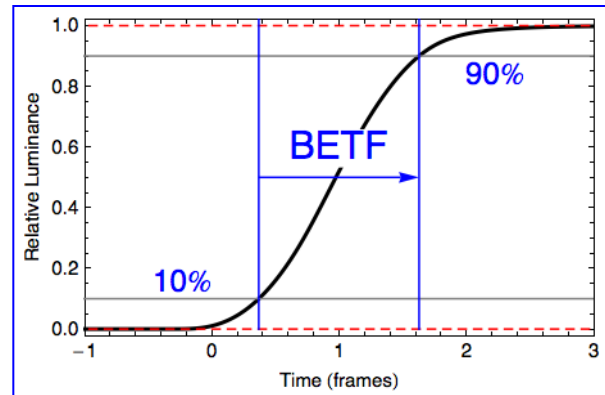


Figure 7. Analysis of the moving-edge temporal profile (METP) to obtain the blurred-edge time in frames (BETF).

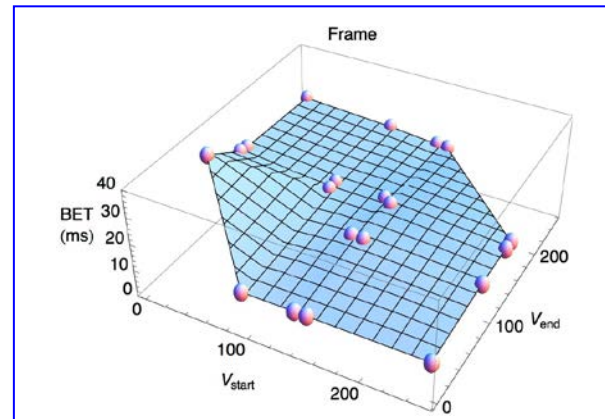


Figure 8. The spheres indicate values of the blur edge time (BET) metric for twenty combinations of V_{start} and V_{end} . Note that in this case the metric increases sharply for the case of $\{V_{start}, V_{end}\} = \{0, 91\}$.

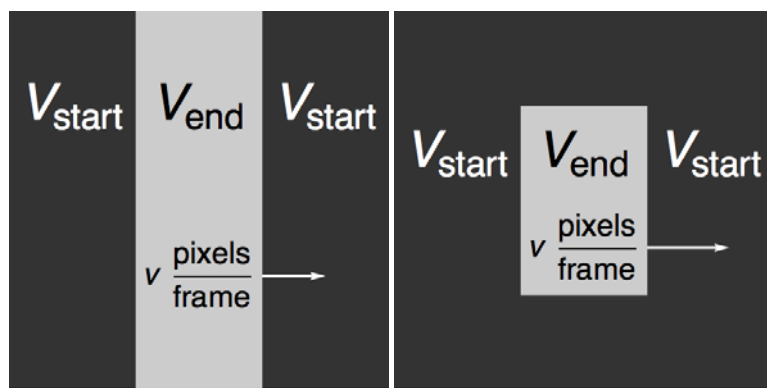


Figure 9. Alternate moving edge blur test patterns: bar (left) and box (right).



But if either of these requirements is violated, there will be distortions in the color in the vicinity of the edge. To measure those distortions, the methods above may be replicated with tristimulus rather than luminance measurements. This will yield, for any particular color pair C_{start} and C_{end} , a set of three METP. An example of this sort of measurement is described below.

At present there are no established procedures for converting those three waveforms into a single metric. Nor are there established recommendations for which color pairs to employ. While a 5x5 or 7x7 array of gray level pairs may suffice in the luminance case, it is probably not practical to consider the 5x5 x 5x5 x 5x5 or larger arrays that a straightforward extension would imply. It should also be noted that if the color primaries have identical temporal properties, it should be possible to estimate color distortions directly from gray level motion-blur measurements.

Moving Line Blur and Moving Grating Blur: This introduction deals primarily with moving edge blur, because that is the predominant measurement at present. However, Moving Line Blur and Moving Grating Blur are two closely related measures, so we discuss them briefly here.

Moving Line Blur: If the bar illustrated in Figure 9 (left) is narrowed sufficiently that the METP or MESP of the two edges overlap, we call the result moving line blur. Typically, the blur will cause a reduction in contrast of the moving line, and if properly quantified that reduction could serve as a measure of motion blur. Moving line blur can be measured with any of the techniques described above (pursuit camera, digital pursuit, or temporal step).

Moving Grating Blur: If a grating is used as the moving test pattern, motion blur will reduce the contrast by different amounts for different spatial frequencies. This allows the blur to be measured in terms of its modulation transfer function (MTF). The general procedure is to move a vertical grating horizontally at a specified speed, and to record the horizontal cross section (the spatial profile) of the tracked image. This can be recorded using any of the image-recording methods described in § 12.3 Moving-Edge-Blur Measurements. If the test image is a sinusoidal luminance grating, the luminance profile during tracking will be sinusoidal as well, and the ratio of its amplitude to that of the input grating is a measure of the MTF (§ 12.5.2 Dynamic MTF). In theory, this quantity can also be obtained from the moving-edge spatial profile (MESP) as described below in § 12.2 Moving-Edge-Blur General Method.

Standard Test Conditions: The specific conditions for each measurement are given in each measurement below, but we note a few general conditions here. Where possible, measurements should be made with the display driven at its native spatial resolution and frame rate. Where a bar or a box is used, height must be large enough to ensure that the measurement aperture is filled, and width must be large enough to avoid overlap between responses to leading and trailing edges. Temporal integration over a number of successive frames may be employed to reduce the noise level, as long as this integration by itself does not alter the shape of the moving-edge spatial profile (MESP).

Apparatus to Acquire Motion-Blur Data: We include short descriptions here of a number of ways motion-blur data can be obtained. More detailed discussions follow in the image-recording methods in § 12.3 Moving-Edge-Blur Measurements.

Pursuit Camera: Conceptually, the simplest measurement of moving-edge blur uses a pursuit camera that smoothly tracks the moving edge. By “smoothly” we mean that the camera fixation point travels at a continuous speed of v px/frame, centered on the edge. This may be accomplished by mounting the camera on a linearly translating stage, or by pivoting the camera, or by moving the display relative to a stationary camera and using other methods. In any case, the camera is simulating the motion of the eye as it smoothly tracks the apparent position of the edge. The result, after averaging over time, is a picture of the blurred edge. After averaging over the vertical dimension (orthogonal to the motion), a one-dimensional waveform representing the cross-section of the blurred edge can be obtained. This is the moving-edge spatial profile (MESP). The moving-edge temporal profile (METP) can be obtained by scaling the moving-edge spatial profile (MESP) by the speed of motion of the edge. See § 12.3.1 Motion Blur from Pursuit Cameras for a description of a pursuit camera system.

Time-Domain-Integration-Camera: This method employs a special fixed camera called a time-domain-integration (TDI) camera that captures charge from the imaging array to emulate the movement of a pursuit camera. See § 12.3.2 Motion Blur from TDI Cameras.

Digital Pursuit with a Fast Camera: This method employs a stationary camera with a shutter speed that is a small fraction of the frame period. With a sufficiently high shutter speed, it is possible to capture a sequence of frames, that, with appropriate shifting and adding, can also simulate the motion of the eye and thus yield a record of the moving-edge spatial profile (MESP), and thereby the moving-edge temporal profile (METP). The stationary camera avoids the mechanical challenges of the pursuit camera. We call this method “digital pursuit.” See § 12.3.3 Motion Blur from Digital Pursuit for descriptions of digital pursuit systems.

Temporal Step: This method employs a fixed non-imaging detector such as a special purpose photodiode or photomultiplier tube (PMT) that measures the temporal step response (TSR) to a gray level transition (Figure 2). This temporal step response (TSR) is then convolved with a pulse of duration equal to the hold time (typically one frame) to obtain an estimate of the moving-edge temporal profile METP. This method is illustrated in Figure 6. This last method relies on an assumption that all pixels are spatially independent. It has been demonstrated to be accurate in many cases but may fail when motion-dependent processing is present. See § 12.3.4 Motion Blur from Temporal Step Response for a description of the moving-edge temporal profile (METP) from the temporal step response (TSR).



12.2 MOVING-EDGE-BLUR GENERAL METHOD

DESCRIPTION: Measure the apparent blur of a vertical grayscale edge as it moves horizontally with a fixed speed. The measurements estimate the appearance of the edge to an eye that tracks the edge with constant speed. The result of the measurement is a one-dimensional waveform with a vertical coordinate of relative luminance and a horizontal coordinate of time—moving-edge temporal profile (METP). The waveform is then analyzed to extract parameters that define the magnitude of the blur. **Units:** frames or ms for time, Hz for frame rate, pixels for image coordinates; **Symbol:** w = frame rate (Hz), v = edge speed (px/frame), p = sample location on display (px, display pixels), f = sample location (frames), τ = time interval between samples in number of frames, V = set of gray levels, M = number of gray levels, V_{start} = starting gray level, V_{end} = ending gray level, $R(f)$ = relative luminance at time sample f (in frames) in the moving-edge temporal profile (METP).

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE:

Measurement of moving edge blur consists of two steps: (1) capture of the moving-edge temporal profile (METP), and (2) analysis of the METP to extract useful metrics. This is a general method.

1. **Select gray level set.** Select a set of M gray levels V spanning the range from V_k to V_w . These may be equally spaced in gray level, in luminance, or in lightness (Appendix § B26 Perceptively Equal Gray-Shade Intervals). One example of equal lightness steps are the gray levels $V = \{0, 56, 91, 139, 170, 212, 255\}$. Another possible set is $V = \{0, 63, 127, 191, 255\}$. If $M = 2$, then $V = \{V_k, V_w\}$, typically $\{0, 255\}$. The set of gray levels are used to create a matrix of gray-to-gray transitions, from V_{start} to V_{end} , where the two grays are drawn from the set V . In the example pictured in Fig. 3, this yields a matrix, with $M(M - 1) = 7 \times 6 = 42$ non-zero transitions.
2. **Select speed.** Select an edge speed of v in pixels per frame (px/frame, an integer). This should be fast enough to test for motion blur but slow enough to be pursued by the measurement instrument. The precise speed is usually not critical since the most metrics correct for speed. We recommend a speed of 8 px/frame.
3. **Create a moving edge.** Select a pair of gray levels V_{start} and V_{end} , from the array shown above. Create a vertical edge consisting of a transition between uniform areas of gray levels V_{start} and V_{end} and scroll horizontally at a speed of v px/frame. The direction of motion should be such that at a point the transition over time is from V_{start} to V_{end} . An example is shown in Fig. 1.
4. **Capture the Moving Edge Temporal Profile.** There are several general approaches to capture of the profile discussed previously in § 12.3 Moving-Edge-Blur Measurements. In the case of a pursuit camera, the camera tracks the edge with a constant speed v . The camera shutter time is set to an integer number of frames. The resulting picture is the pursuit image of the edge. The pursuit image is averaged over rows, to yield a waveform that estimates the horizontal spatial profile of the blurred luminance edge that would be seen by an eye moving with fixed speed v . This is called the moving-edge spatial profile (MESP). The horizontal coordinate of the MESP should be expressed in terms of display pixels p , if necessary, by converting sample coordinates from camera pixels to display pixels, using the camera magnification m . This profile is then re-scaled horizontally by converting each spatial sample location p in pixels to a time f in frames by the formula

$$f = p / v.$$

This yields a list of numbers $R(f)$ corresponding to relative luminance at a sequence of points in time. Usually, these points are regularly spaced with a sample interval of τ frames. We call this the

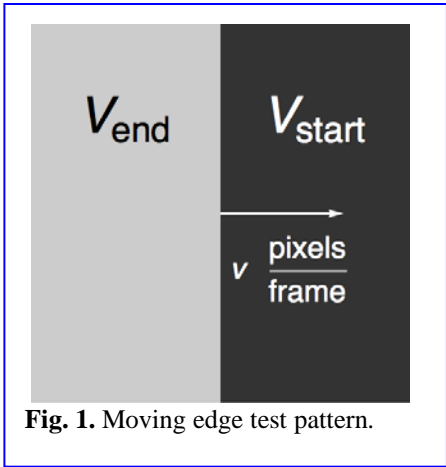


Fig. 1. Moving edge test pattern.

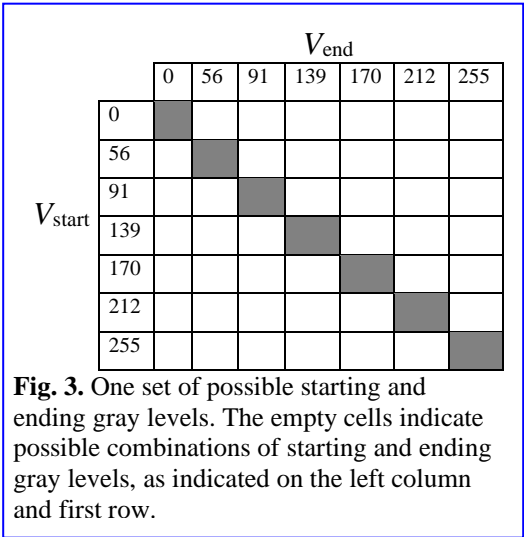


Fig. 3. One set of possible starting and ending gray levels. The empty cells indicate possible combinations of starting and ending gray levels, as indicated on the left column and first row.



moving-edge temporal profile (METP). An example is shown in Fig. 2.

5. As noted, the moving-edge temporal profile (METP) can also be captured by other methods (see § 12.3 Moving-Edge-Blur Measurements). Whichever method is used, it should ensure that the time step $\tau \leq 0.05$ frames.
6. **Repeat the measurement at each $\{V_{\text{start}}, V_{\text{end}}\}$ transition.** This will yield an array of $M(M - 1)$ waveforms. This array will include both rising and falling transitions.

ANALYSIS: In general, the goal of the analysis is to convert each moving-edge temporal profile (METP) to a single number (a metric) that characterizes the magnitude of the blur. Several metrics are in use or have been proposed. Most of the metrics are measures of the width of the blur. One example is the blurred-edge time (BET), which consists of the time in milliseconds between the 10% and 90% points of the waveform. Another examples is Gaussian edge time (GET), a similar but more robust metric. The following metrics defined below are discussed in following measurement sections:

- BET—Blurred edge time
- EBET—Extended blurred edge time
- PBET—Perceived blurred edge time
- BEW—Blurred edge width
- BED—Blurred edge degrees
- EBEW—Extended blurred edge width
- GET—Gaussian edge time
- MTB— Motion Temporal Bandwidth
- MSB— Motion Spatial Bandwidth
- JND—Just noticeable difference

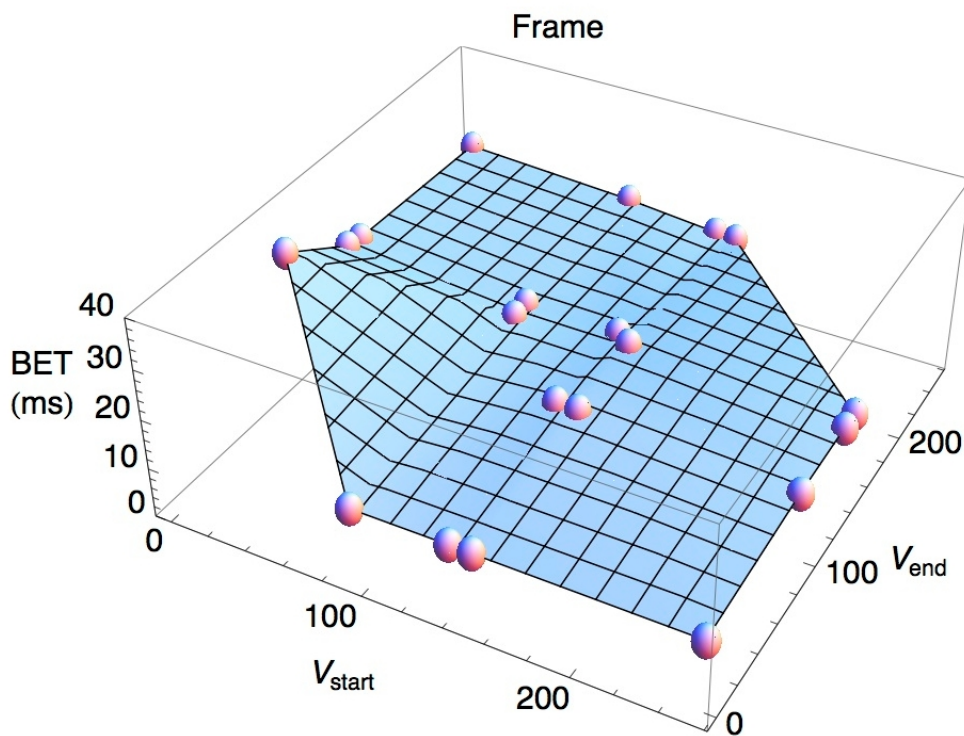
Whatever metric is chosen, it is computed for each of the the $M(M - 1)$ different gray-gray transitions. An example result is shown in Fig. 4, plotted as points on a surface. The axes are starting and ending gray levels.

A final step in the analysis is to summarize the set of measurements obtained from the $M(M - 1)$ different gray-gray transitions. This summary should include both the mean value and the standard deviation. The maximum and minimum may also be reported.

REPORTING: Reporting should include the gray levels V , the edge speed v in px/frame, the frame rate w in Hz, the sample interval τ in frames, and the moving-edge temporal profile (METP) and/or derived metrics such as B_{BET} or B_{GET} (see sections below) for each $V_{\text{start}} - V_{\text{end}}$ transition. If an array of gray-level pairs is used, the array of metric values may be reported or summary statistics derived from them in addition to reporting them graphically (Fig. 4). The moving-edge temporal profile (METP) should be reported in tabular form or graphically or both.

COMMENTS: (1) Independence of collection and analysis: The methods of collecting and analyzing the moving-edge temporal profile (METP) are largely independent. Thus, it is possible to use any of the collection methods with any of the analysis methods.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting example:		
V_{start}	0	gray level
V_{end}	255	
τ	0.05	frame
w	60	Hz
v	8	px/frame
B_{GET}	10.7	ms
METP Follows: $R(\text{frame \#})$		
$R(1)$	131.5	relative luminance
$R(2)$	131.5	
$R(3)$	131.6	
...



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

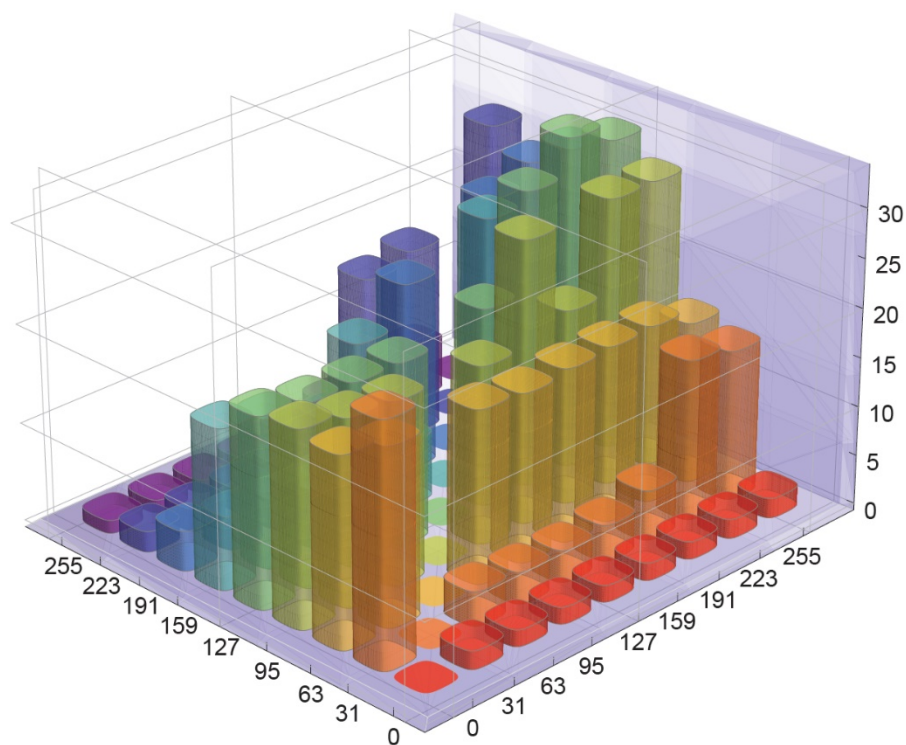


Fig. 4. Examples of blurred-edge time (BET) for a sample display plotted as a function of starting and ending gray levels.



12.3 MOVING-EDGE-BLUR MEASUREMENTS

The moving-edge temporal profile (METP) is a useful measure of moving edge blur, but it is a waveform, and thus difficult to report as a single number or to rank order. Therefore, it is useful to summarize the METP by means of one or several of the simple metrics described in several of the following sections. Each simple metric is a type of analysis of the waveform that usually resulting in a single number. Using such simple numerical metrics, when waveforms are collected for several gray-gray transitions there will be one simple numerical result for each waveform. We also offer a method of combining these multiple results, and also a metric to summarize the moving-edge tristimulus temporal profile (METTP). The first two sections provide two ways that the METP can be determined.

12.3.1 MOVING-EDGE BLUR FROM PURSUIT CAMERAS

DESCRIPTION: We measure the moving-edge blur using a pursuit camera. The camera motion may be achieved by rotation or by a linear translation. A view of a camera is oriented in such a way as to track a moving edge as it travels across the screen—the camera can be rotated, a mirror can be rotated giving the axial camera a rotational view, and the camera can be linearly moved to follow the motion (see Fig. 1). If a rotational pursuit is chosen, the picture should be taken when the moving pattern is closest to the camera (at the position of the normal from the camera pivot). A temporally integrated image or sequence of images of the edge is captured. These pursuit images mimic the image that would appear on the retina of a human eye as it pursued the moving edge. If a sequence of images is used, then the images are averaged over frames and over rows to obtain an estimate of the moving edge spatial profile (MESP). The spatial coordinate (pixels) is divided by the edge speed (px/frame) to obtain the moving edge temporal profile (METP). The camera exposure (shutter speed) should always be in increments of the frame period of the display. The configuration of the pursuit camera can be simple where trial-and-error methods are used to capture the appropriate image. The apparatus can also be sophisticated and automated.

Figure 2 shows an overview example of a rather sophisticated automated measurement system that includes the following components. This is for illustration purposes only of what can be required for an automated system—it suggests some of the things that can or must be considered in using such systems. Our detailing this apparatus in no way suggests its suitability or requirement for making motion-blur measurements. Possible patents may apply to such systems. (1) **A video signal generator:** It generates test patterns for the display. The video signal generator has a control unit for test pattern selection and start-stop of the measurement procedures. The output interface of the video signal generator is suitable for connection to the DUT (e.g., LVDS, DVI, or HDMI). It should also include a trigger signal to start the data acquisition process. In some cases, a high-quality computer video card can be used for the generated image. (2) **Trigger signal:** Either a data acquisition board can be used to detect a digital trigger signal from the generator, or an optical trigger can be arranged that detects the moving pattern. (3) **Motion control:** A motion control board can control the motor movements through position feedback and control signals. (4) **Array camera and rotating mirror:** A fixed array camera with a rotating mirror that deflects the image of the DUT so that the image of the edge is stationary on the camera. The camera and mirror operate in sync with the commands from the control system to track and acquire moving images displayed on DUT. It is also possible to use a rotating camera or a translating camera in a similar way. (5) **Frame-grabber board or image**

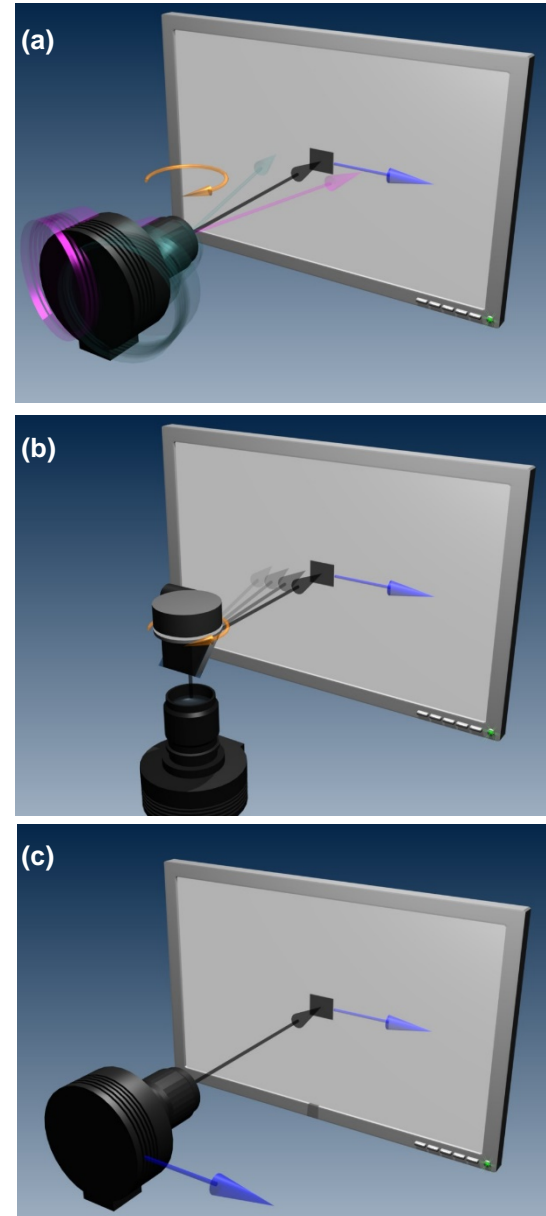


Fig. 1. Pursuit-camera configurations: (a) rotation of the camera (this illustration depicts a vantage-point configuration whereby the camera always peers through the same point in space), (b) fixed camera with a rotating mirror, and (c) linear pursuit.



download: The resulting images are downloaded through a camera link interface (and possible specialized computer board) and transferred to the computer for further processing. **(6) Shutter speed (exposure), camera iris, focus, and pursuit speed:** The shutter speed of the camera (also its exposure in seconds) is set to be an integral multiple of the frame period of the display. The iris of the camera is set to accommodate the range of the luminances of the display, that is, to provide a linear representation of the luminance for the full range of luminances present in the pattern. The camera lens should be focused on the display surface where the image is captured; for a rotational camera or mirror the focal point should be at the orthogonal position of the rotation. The pursuit speed of the camera must be equal to the scroll speed of the moving pattern.

PROCEDURE: This is a typical procedure in using a specially designed pursuit camera in a darkroom. There are other apparatus and methods that work as well. This is just an example. These measurements should be made in a darkroom. An spreadsheet template is available at

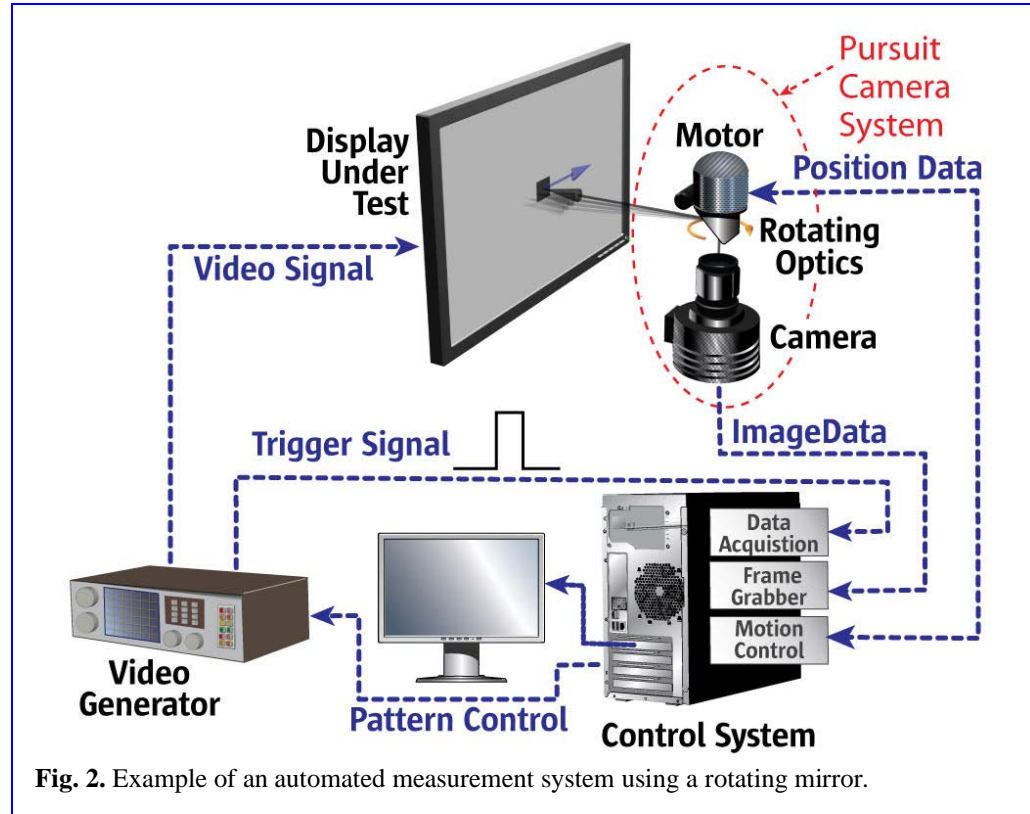


Fig. 2. Example of an automated measurement system using a rotating mirror.

<https://doi.org/10.55410/epxc8920>, which shows an example of some of the calculations. Be sure to avoid moiré patterns by using many camera pixels per display pixel (10 to 20 or more helps).

1. Follow general procedures for moving edge blur measurement described in § 12.2. Moving-Edge-Blur General Method.
2. Select gray levels V_{start} and V_{end} .
3. Select edge speed v (integer) in px/frame. A recommended value is 8 px/frame.
4. Produce moving edge between V_{start} and V_{end} moving at speed v on the sample display.
5. Set shutter speed of the camera to an integer frame period. A typical value is four frames.
6. Adjust camera iris and focus.
7. Adjust pursuit speed of the camera to equal the speed of the image on the sample display (see diagnostics below).
8. A moving test pattern from the video signal generator (or computer video card if so equipped) is displayed on the DUT and the control system waits for the trigger signal—this assumes an automated apparatus as in Fig. 2.
9. When the trigger signal is received, the motion control board is activated, and the motor is rotated to track the moving test pattern on the DUT.
10. When the moving edge reaches the center of the DUT, the image, $S(c_{\text{col}}, c_{\text{row}})$, of the sample display is captured, where c_{col} is camera image column, and c_{row} is camera image row.
11. If you are using a system that does not have flat-field-corrections (FFCs) for all the camera settings as well as backgrounds, then you may have to obtain a flat field of the display $F(c_{\text{col}}, c_{\text{row}})$ by setting the display to white and capturing the image. If the display is not sufficiently uniform, you may need to use a uniform source to obtain the FFC. In such a case, use the camera settings that are used for taking the picture of the display by adjusting the uniform source to the same luminance.
12. If a background (dark-field exposure) is not already provided with the camera system, capture a dark field $D(c_{\text{col}}, c_{\text{row}})$ by placing a lens cap on the lens of the camera and acquiring a dark-field exposure. Only if the display is truly black can you use the display showing black to acquire a dark field. If the display is not absolutely black, then that black luminance



level can be part of the image acquired by the camera in making blur measurements and a separate dark field will be needed using the lens-cap method of acquisition.

13. Correct for camera lens profile in the pursuit image by flat field and dark field. The pursuit image $P(c_{\text{col}}, c_{\text{row}})$ is obtained from $S(c_{\text{col}}, c_{\text{row}})$ by correcting for the camera characteristics:

$$P(c_{\text{col}}, c_{\text{row}}) = \frac{S(c_{\text{col}}, c_{\text{row}}) - D(c_{\text{col}}, c_{\text{row}})}{F(c_{\text{col}}, c_{\text{row}}) - D(c_{\text{col}}, c_{\text{row}})} \quad (1)$$

14. Obtain the spatial profile $R(c_{\text{col}})$ in terms of camera pixels (columns) by averaging the pursuit image over an appropriate number (N) of rows,

$$R(c_{\text{col}}) = \frac{1}{N} \sum_{r=1}^N P(c_{\text{col}}, c_{\text{row}}) \quad (2)$$

15. Compute the moving-edge spatial profile (MESP) $R(p)$ by converting the spatial coordinate c_{col} (camera pixels, cpx) to p (display pixels, px) via the camera magnification m (camera pixels/display pixels, cpx/px): $p = c_{\text{col}}/m$ (in units of display pixels, px).
16. Compute the Moving Edge Temporal Profile (METP) $R(f)$ by dividing the horizontal pixel coordinate p by the speed of the moving edge v : $f = p/v$ (units of frames, time measured in frames).

SPECIAL REPORTING: It is helpful to report the exposure time (also called the shutter time) in seconds and in number of frames. It is also helpful to report the size of the display or camera pixel (or both) and the ratio between them.

DIAGNOSTICS: Several diagnostics are useful to check the performance of the pursuit system. These are not required, but they may help determine if problems exist.

Smoothness of Tracking from Slit

Observations: How smooth the camera tracking is can be investigated by replacing the display with a vertical slit on a uniform source—see Fig. 3. If the tracking is smooth, the resulting image will be smooth and have no irregularities in it.

Minimal Blur Speed Matching: If the tracking speed of the camera can be changed gradually, then a number of images can be obtained using the same exposure settings but taken at different tracking speeds from too slow to too fast. The resulting sequence of images will exhibit blur widths of different sizes. The most correct speed of the camera will produce the smallest size of the blur in the image. Such a diagnostic can provide a check for the correct speed of the pursuit camera. This is particularly useful for less sophisticated systems where it is not possible to accurately register the motion of the camera—either linear or rotational—with the moving pattern.

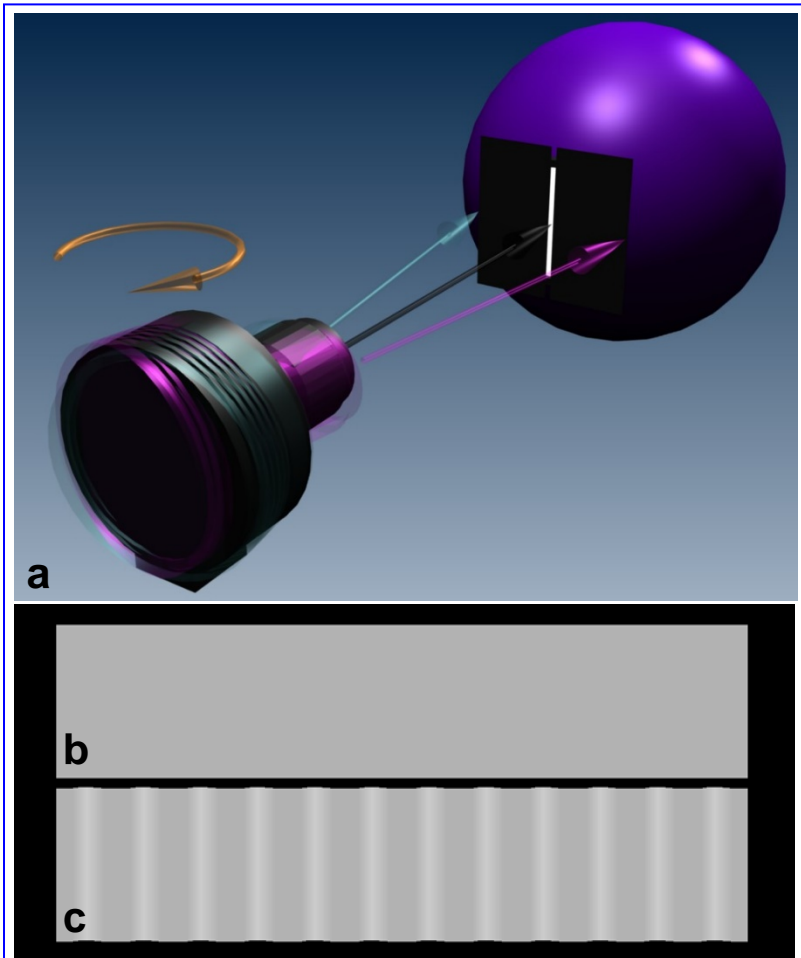


Fig. 3. Diagnostic using a slit on a uniform source to test smoothness of tracking (a). The bottom two tracking images show a smooth pursuit at the top (b) and irregular pursuit at the bottom (c).



12.3.2 MOVING-EDGE BLUR FROM TDI CAMERAS

DESCRIPTION: A time-domain integration (TDI) camera provides another means of obtaining pursuit images for motion artifact analysis. Using this measurement method the camera and the display remain stationary during the measurement. A scrolling image is displayed on the DUT and the TDI camera is adjusted to electronically move the charge being accumulated on the CCD in synchrony with the moving image. This charge movement across the CCD emulates the movement of a pursuit camera without the need for mechanical motion (see Fig. 1). At the end of the exposure period the pursuit image is read from the camera and processed to obtain the moving-edge temporal profile (METP).

OTHER SETUP CONDITIONS: Two types of time-domain integration (TDI) camera may be used: Full-frame TDI (TDI line-scan cameras) and partial-frame TDI cameras. Full-frame TDI cameras place restrictions on the lens magnification, such that an integer multiple of camera pixels is imaged on to a display pixel, as noted below. The partial frame TDI camera does not have these restrictions.

PROCEDURE

1. Set the camera shutter speed Δt to be an integer multiple of the DUT frame period T (i.e., $\Delta t = T, 2T$, or $3T$, etc.) and adjust the camera iris to achieve good dynamic range. If the image is too dim adjust the shutter speed to the next multiple of the frame period.
2. Position the camera; adjust working distance and focus to achieve the desired magnification.
3. Adjust the camera rotation such that the TDI scanning is in the direction of image motion.
4. Display a stationary test pattern of known size (vertical bar or box test pattern) and capture the test pattern in non-TDI mode (normal camera imaging mode).

Calculate the camera magnification m as a ratio of the number of camera pixels in the resulting image N_c to display pixels in the original bar N_d : $m = N_c/N_d$.

5. For moving images, set the TDI shift frequency f_{TDI} in camera pixels per second to match the velocity v of image motion on the display screen in display pixels per frame assuming frame rate w in frames per second and with magnification m :

$$f_{TDI} = vwm$$

For example: $v = 16$ px/frame, $w = 60$ Hz, $m = 4$ gives $f_{TDI} = 16 \text{ px/frame} \times 60 \text{ Hz} \times 4 = 3840 \text{ Hz}$.

Note: the shutter speed cannot be independently controlled on full-frame TDI cameras; magnification and TDI scan frequency must be adjusted to achieve the desired effective shutter speed. The magnification of the camera must be adjusted such that the TDI dimension of the CCD images an integer number of display jump regions. This satisfies the shutter speed requirement of Step 1. For example: with a DUT scroll speed of $v = 16$ px/frame and TDI camera width of 64 px the magnification m should be set to exactly 1, 2, 3, or 4. In this case the magnification could not be greater than 4 because the entire jump region would no longer be imaged onto the CCD. Partial frame TDI cameras don't have this limitation and allow independent setting of magnification and shutter speed.

The image acquired by the TDI camera is a pursuit image. It can be analyzed and processed using the same techniques as images acquired by mechanical pursuit cameras. One edge of the partial-frame TDI image will be partially exposed. This edge should be cropped before further analysis. The pursuit image can be converted to the moving-edge temporal profile (METP) by averaging over rows, converting from camera pixels to display pixels, and converting from pixels to frames by dividing by the speed in px/frame.

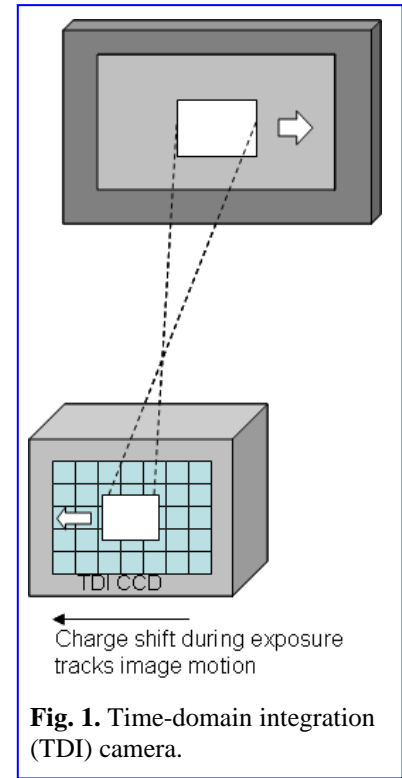


Fig. 1. Time-domain integration (TDI) camera.



12.3.3 MOVING-EDGE BLUR FROM DIGITAL PURSUIT

DESCRIPTION: We measure the motion blur using a fast stationary digital camera to simulate a pursuit camera. In digital pursuit a sufficient number of images of a moving target are made, and the movement is seen as a shift in position of the target. By analyzing the static images of the resulting luminance profiles, the equivalent of pursuit eye tracking can be calculated. The moving edge spatial profile (MESP) can then be determined, which can then be converted to other metrics that characterize the moving-edge blur.

SPECIAL SETUP CONDITIONS: Two camera types are known: the high-speed camera and the trigger-delay camera. Both types must have a high sensitivity to capture images with very fast shutter speeds. As the luminance of the DUT is integrated during one sub period, this time period must be short enough to capture luminance details like overshoot, undershoot, ripples or other artifacts. The cameras can use (optionally) an external trigger (V-sync from the video generator or from an optical trigger device) for synchronization.

Both camera types capture a number of images, N , with a shutter speed of $t_{sh} = T/N$; so the images, with respect to time, will cover a full frame period of T . The high-speed camera captures the N images within one frame period (Fig. 2), while the trigger-delay camera captures the N images in separate frame periods (Fig. 3).

The target can include several edges, but the basic target is an edge moving with a constant speed of v in px/frame. Measurements with fast shutter speeds might give a poor signal to noise ratio. The signal to noise ratio can be improved by repeating the measurement. For the trigger-delay camera, the movement of the target must be repeated as the trigger-delay camera has to 'catch' the target at the same position on the display. The movement is restricted to move through a fixed number of frame periods and then repeated.

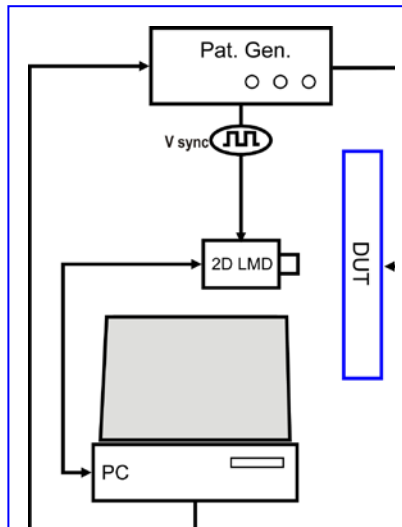


Fig. 1. Apparatus with optional sync. for the camera (LMD).

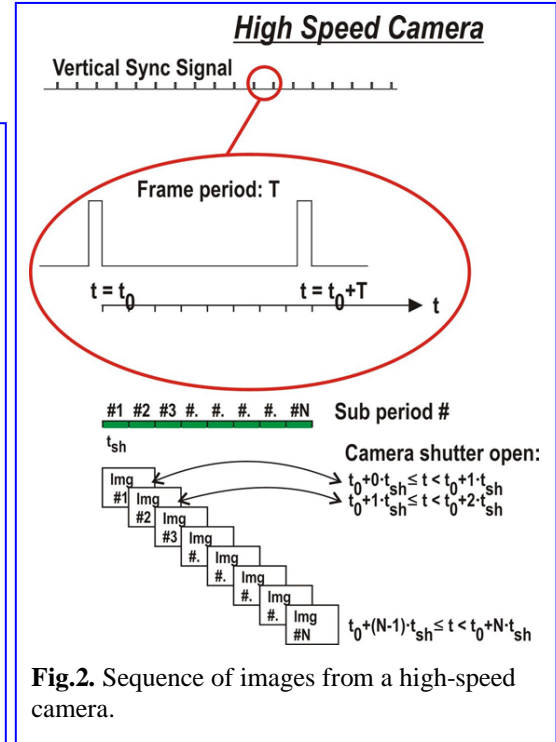


Fig. 2. Sequence of images from a high-speed camera.

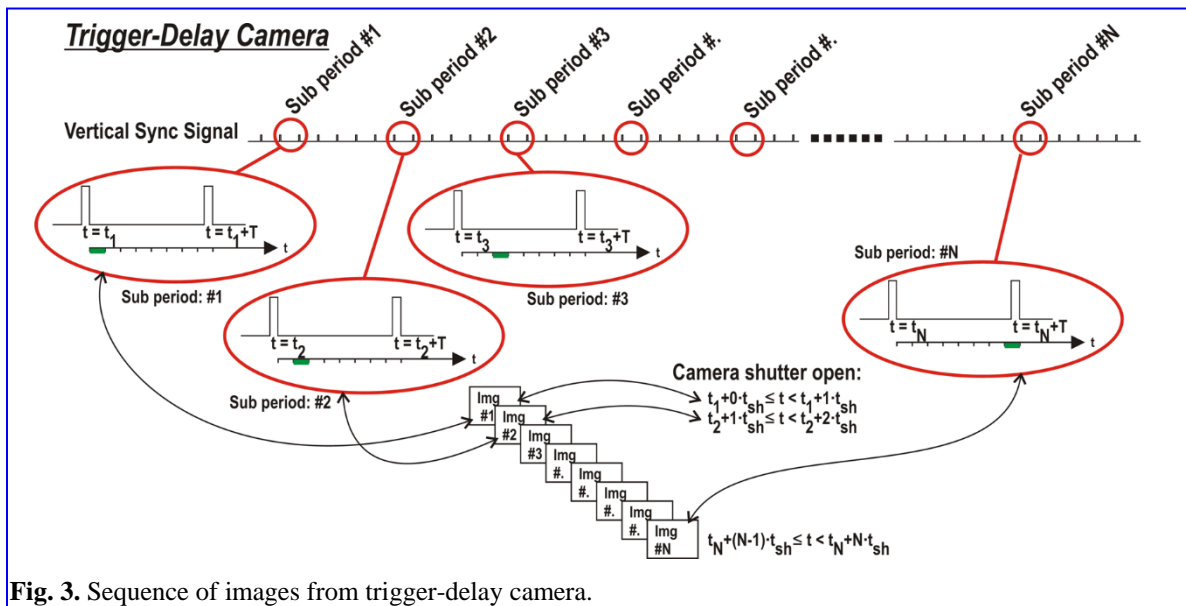


Fig. 3. Sequence of images from trigger-delay camera.



PROCEDURE: If a dedicated measurement system is used for this measurement, then follow the instructions given in the manual. This will include:

1. Select the gray levels for the edge
2. Setup the generator for displaying and moving the target
3. Select the number of images, N , to cover a single frame period
4. Acquire the N images

ANALYSIS: Each of the $n = 1, 2, \dots, N$ images holds $1/N$ of the luminance information in a frame period. Adding the N images pixel by pixel would result in an image as taken with a shutter speed (exposure) of T (the frame period) in seconds.

It is assumed in smooth pursuit eye tracking that the fixation point of the eye will move with a constant speed corresponding to v , the eye will move v/N pixels per frame in each of the $n = 1, 2, \dots, N$ images. See the blue dotted line, indicating the eye fix position, on figure on the right. If the pixels in the N images are shifted mv/N pixels per frame, where m is 0 for the first image, 1 for the next, \dots and $N - 1$ for last image, as indicated in Fig. 4, the eye fixation point is aligned for all the images. By adding the N shifted images pixels by pixel we obtain the pursuit image. Averaging this image over rows will yield the moving edge spatial profile (MESP). Converting the spatial coordinate to time in frames by dividing by the speed in px/frame will yield the moving edge temporal profile (METP).

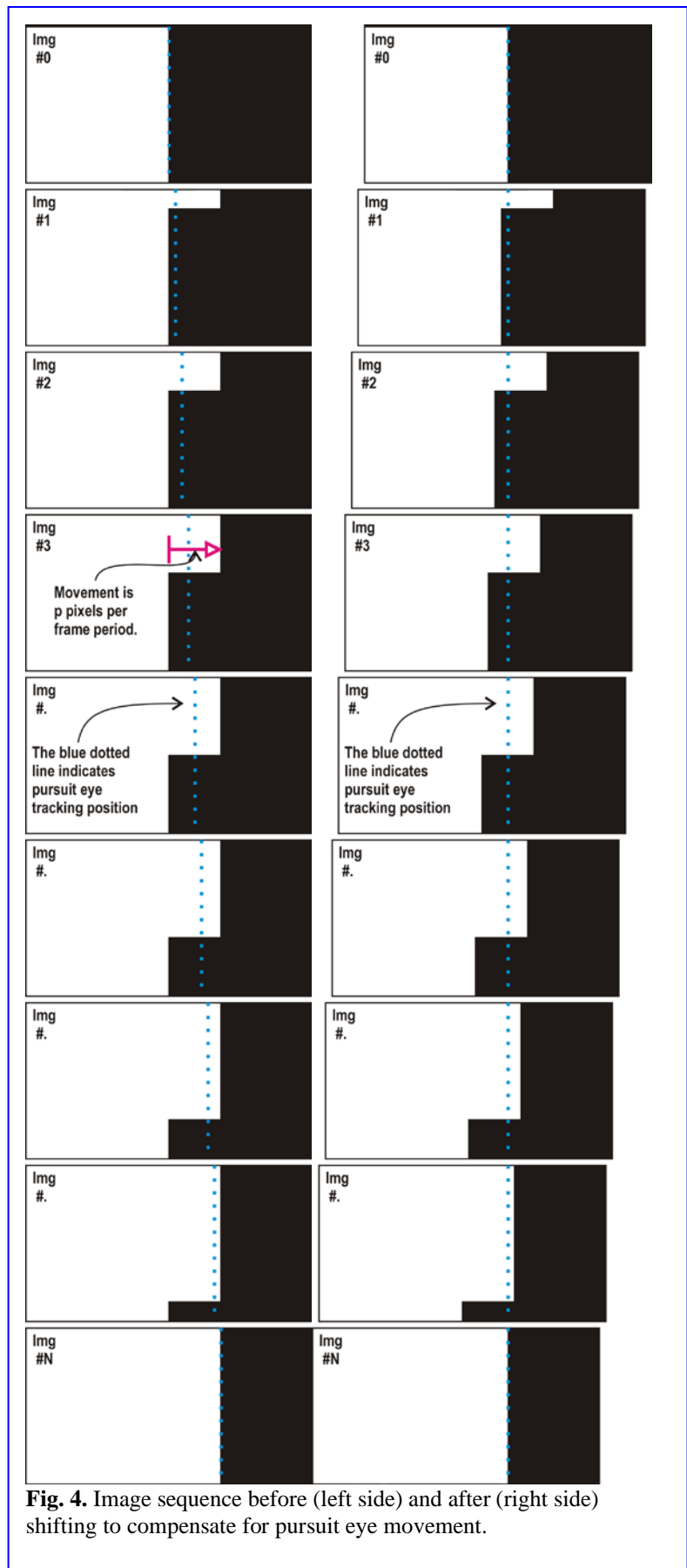


Fig. 4. Image sequence before (left side) and after (right side) shifting to compensate for pursuit eye movement.



12.3.4 MOVING-EDGE BLUR FROM TEMPORAL STEP RESPONSE

DESCRIPTION: Estimate the moving edge temporal profile (METP) from the temporal step response (TSR) of the display. The TSR is convolved with a pulse of width one frame, to produce the METP. **Symbol:** $R(f)$

PROCEDURE: Our notation is: f is time sample location in frames, τ is sample interval in frames, v is speed in px/frame, Π is the unit pulse function, and \otimes is for convolution.

1. Select starting and ending gray levels V_{start} and V_{end} , and a time step τ in frames.
2. Measure the temporal step response (TSR) of the display during the transition from gray level V_{start} to V_{end} (see § 10.2.1 Temporal Step Response). The result of that measurement can be a sequence $S(f)$ of relative luminance values at sample intervals of τ frames. (See comment #2 below for the conversion from time to frames.)
3. Convolve the TSR sequence with the temporal aperture function, which is the on period within the frame time. The result of the convolution is the moving-edge temporal profile (METP). This process is illustrated in the Fig. 1. To preserve the magnitudes of the relative luminance values, a pulse with integral of one should be used. The formula for moving-edge temporal profile (METP) is given by

$$R(f) = S(f) \otimes \Pi(f), \text{ or}$$

$$R(f) = \int_0^f S(g) \Pi(f - g) dg$$

where R is the moving-edge temporal profile (METP), $S(f)$ is the temporal step response (TSR), $\Pi(f)$ is the unit pulse function, \otimes is for convolution, and f is time in units of frames.

4. (Optional) Compute the moving-edge spatial profile (MESP) for a given moving-edge speed v by changing the horizontal coordinate of the moving-edge temporal profile (METP) from frames to pixels by multiplying each coordinate by the speed v in px/frame.

COMMENTS: (1) **Hold Time.** If the hold time of the display is less than one frame, then the pulse width should be equal to the hold time. (2) **Conversion from Temporal Response:** The measurement and any required smoothing from the response-time measurement in § 10.2.1 Temporal Step Response results in a series of relative luminance measurements L_i for $i = 1, 2, \dots, N$ over N intervals of duration $\Delta t = 1/s$ (seconds per sample), where s is the sample rate of the detector in samples per second. To perform the above analysis, we must convert this temporal profile, L_i , to the sequence $S(f)$ in terms of frames and not time. To make the conversion, we need the frame rate w in frames per second (or Hz). Then $\tau = \Delta t w$ (frames/sample). The above starting sequence $S(f)$ may be written as

$$S_i = S(f_i) = \{L_i, i = 1, 2, \dots, N, \text{ where } f_i = i\tau\}.$$

And then the above convolution is given by

$$R_i = R(f_i) = \sum_{g=f_1}^{f_i} S(g) \Pi(f_i - g).$$

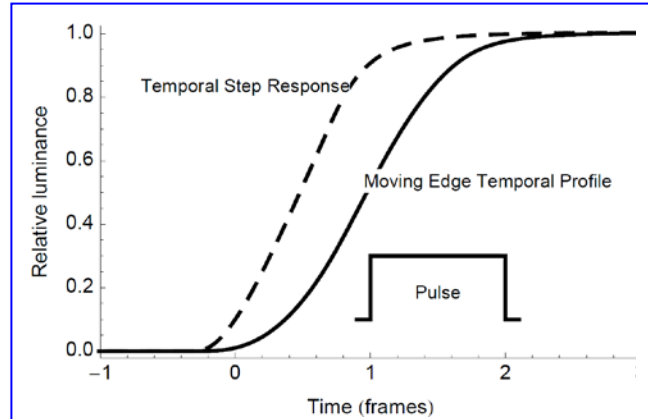


Fig. 1. Illustration of obtaining the moving-edge temporal profile (METP) from the temporal step response (TSR).



12.3.5 COLOR MOVING-EDGE BLUR

DESCRIPTION: Color distortions in a moving color edge are measured by conducting measurements of moving edge blur for a moving edge between two colors, $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} , in three tristimulus color channels X , Y , and Z : $\mathbf{C}_{\text{start}} = (X_{\text{start}}, Y_{\text{start}}, Z_{\text{start}})$ and $\mathbf{C}_{\text{end}} = (X_{\text{end}}, Y_{\text{end}}, Z_{\text{end}})$, which are three-component vectors in the tristimulus color space. These measurements are recorded as moving-edge temporal profile (METP) for each of X , Y , and Z . Together, the three tristimulus METPs comprise the moving-edge temporal tristimulus profile (METTP), which can be used to construct metrics of moving edge color blur.

If the several color primaries of a display exhibited identical motion blur, and if that blur did not depend upon the magnitude of the transition, then when an edge between two colors ($\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end}) moved, there would be blur, but no color distortion. Instead of a sharp transition between two colors there would be a gradual transition along a straight line in chromaticity space. All colors on the screen would be linear combinations of the two colors $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} . But if either of these requirements is violated, there will be distortions in the color in the vicinity of the edge. Figure 1 shows in a chromaticity diagram the locus of points in the edge transition, showing that there are departures from the straight line between the two colors.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The general setup conditions are as for Moving Edge Blur (12.3.2). The LMD must be capable of providing measurements of X , Y , and Z . The basic target is a vertical edge between two selected colors $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} moving with a constant speed of v in px/frame (see Fig. 2).

PROCEDURE: Use an appropriate method to obtain the moving-edge temporal profile (METP) for each tristimulus value X , Y , and Z . This set of three waveforms is the moving-edge tristimulus temporal profile (METTP). Figure 3 shows an example of an METTP in which the three tristimulus waveforms are not scaled versions of each other, so distortions will occur. We obtain three tristimulus profiles defining the color transition $\mathbf{C}_i = (X_i, Y_i, Z_i)$ for $i = 1, 2, 3, \dots, N$, where $i = 1$ is for $\mathbf{C}_{\text{start}}$ and $i = N$ is for \mathbf{C}_{end} .

REPORTING: For each edge tested, report the two RGB levels (colors) for $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} , the sampling period τ of the data in frames, the speed v in px/frame, the display frame frequency w (Hz), and the tristimulus values (X_i, Y_i, Z_i) describing the METTP curves. If it is not practical to report the full tabular values of the tristimulus values, then report the METTP curves graphically (as in Fig. 3).

COMMENTS: There are no established recommendations for which color pairs to employ. One option is to use secondary colors (sums of pairs of primaries) since this may showcase any problems. For the sake of a simple illustration, some will want to use RGB profiles rather than tristimulus values.

—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Reporting Example:				
$\mathbf{C}_{\text{start}}$	255	255	0	for RGB
\mathbf{C}_{end}	255	0	255	for RGB
τ	0.05			frames
w	60			Hz
v	8			px/frame

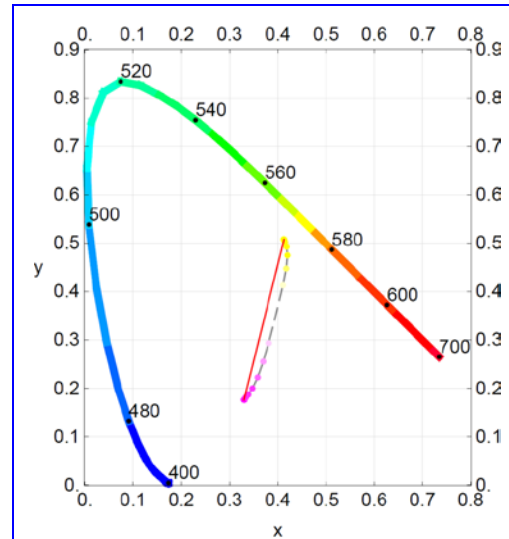


Fig. 1. Locus of chromaticity coordinates of points in the transition between colors. Note that they depart from the straight line between the endpoints, indicating color

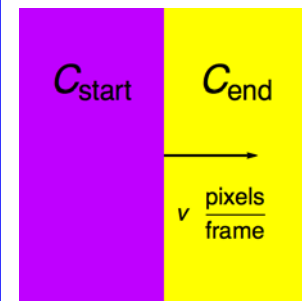


Fig. 2. Color moving edge test pattern.

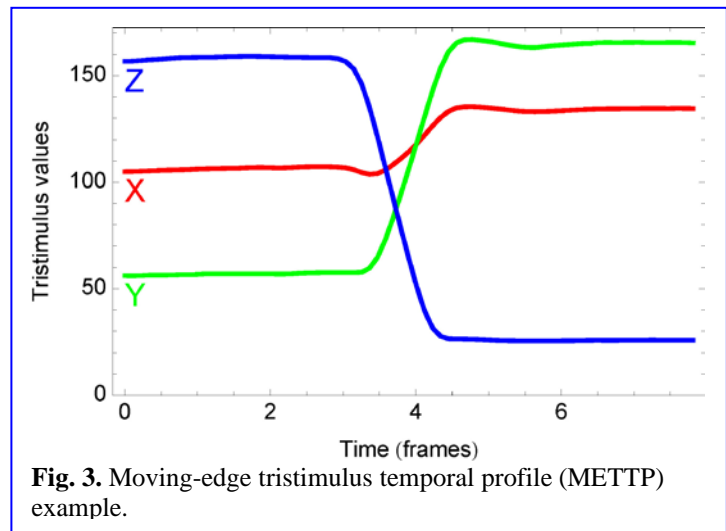


Fig. 3. Moving-edge tristimulus temporal profile (METTP) example.



12.4 MOVING-EDGE-BLUR METRICS

The moving-edge temporal profile (METP), discussed in the previous sections, is a useful measure of moving edge blur, but it is a waveform, and thus difficult to report or to rank order. Therefore, it is useful to summarize the METP by means of one or several of the metrics described in the following sections. Each is a type of analysis of the waveform, usually resulting in a single number. When waveforms are collected for several gray-gray transitions, there will be one metric result for each waveform. We also offer a method of combining these multiple results, and also a metric to summarize the moving-edge tristimulus temporal profile (METTP).

12.4.1 BLUR EDGE TIME

DESCRIPTION: We measure the motion blur by estimating time interval between 10% and 90% of the transition of the moving edge temporal profile (METP). A number of metrics can be defined as a result. **Units:** ms for time, Hz for temporal frequency (frame rate); **Symbol:** v for speed in px/frame, w for frame rate in Hz or frames per second, r for display visual resolution in px/degree, and τ for time measured in frames between moving-edge temporal profile (METP) samples.

PROCEDURE:

1. These metrics begins with a moving-edge temporal profile (METP) captured using an appropriate apparatus (see § 12.2 Moving-Edge-Blur General Method and § 12.3 Moving-Edge-Blur Measurements). This standard waveform will consist of a list of relative luminance values at time intervals of τ frames. It results from motion of an edge, between starting and ending gray levels V_{start} and V_{end} , at edge speed v px/frame. The red points in Fig. 1 show an example of METP values as expressed in samples collected by the apparatus, which exhibits considerable noise.
2. Filter the waveform to remove noise. The blue curve in the Fig. 1 shows an example result of such filtering. This was obtained by convolving the METP with a Gaussian kernel having a standard deviation of eight samples, as shown in Fig. 2. The appropriate kernel depends upon the value of τ and the nature of the noise.
3. Identify 0% and 100% levels (minimum and maximum, or y_0 and y_{100} for relative luminance levels) of the filtered waveform (see Fig. 1).
4. Interpolate the filtered waveform to locate i_{10} and i_{90} that yield the 10% and 90% levels of y_{10} and y_{90} (see Fig. 1).
5. The value of the blurred-edge time in number of samples of the curve (BETS), is the interval between i_{10} and i_{90} (see Fig. 1).
6. The value of blurred-edge time in frames (BETF) is given by

$$B_{\text{BETF}} = \tau |i_{90} - i_{10}|,$$

where τ is the time between moving-edge temporal profile (METP) samples in frames, and i_{90} and i_{10} are the sample numbers at the 10% and 90% points.

7. The value of blurred-edge time (BET) in milliseconds is given by

$$B_{\text{BET}} = \frac{1000 B_{\text{BETF}}}{w} \text{ (in ms),}$$

where w is the frame rate in Hz (or frames/s).

8. (Optional) Compute the extended blurred-edge time (EBET) given by

$$B_{\text{EBET}} = 1.25 B_{\text{BET}}.$$

B_{EBET} is the interval between extension of the line between points $[i_{90}, R(i_{90})]$ and $[i_{10}, R(i_{10})]$ to intersect the 0% and 100% lines (see Fig. 1). These points are called the intercepts.

9. (Optional) Compute the blurred-edge width (BEW) in pixels given by

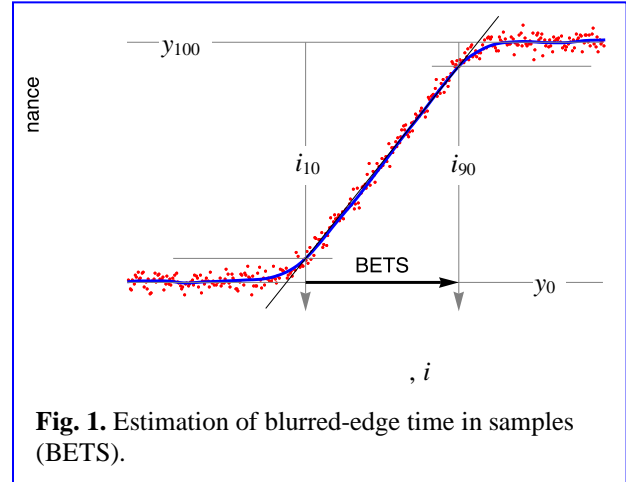


Fig. 1. Estimation of blurred-edge time in samples (BETS).

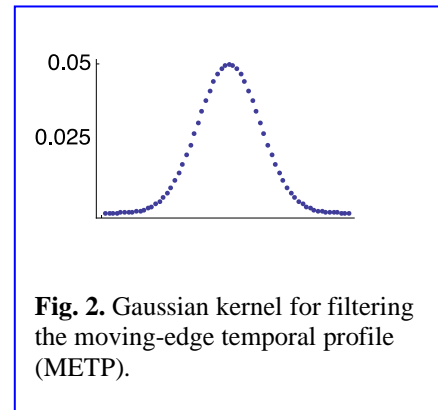


Fig. 2. Gaussian kernel for filtering the moving-edge temporal profile (METP).



$$B_{BEW} = vB_{BETF},$$

where v is edge speed in px/frame.

10. (Optional) Compute the blurred-edge degrees (BED) in degrees of visual angle given by

$$B_{BED} = \frac{B_{BEW}}{r},$$

where r is display visual resolution in px/degree. Therefore, the B_{BED} will depend on the viewing distance.

COMMENTS: (1) Filtering: The kernel should be designed so that it is symmetrical, and the sum of its values is one. **(2) Overshoot and Undershoot:** Calculation of the blurred-edge time (BET) does not reflect overshoot or undershoot. Special rules may be used to adjust BET for overshoot and undershoot. As an example of rules for over and undershoot we include a brief description of the rules from the VESA FPDM2 Update document that discussed motion blur. We define a general blurred-edge variable as B_O for overshoot, B_U for undershoot, and B_{OU} for both over and undershoot, where the B can be any of the above metrics. The following are examples of legacy rules for clearly discernable overshoot and undershoot conditions. Other rules may be of use to all interested parties.

- **Overshoot Only $\leq 10\%$:** If the overshoot relative luminance is less than or equal to 10% of the non-blurred y_0-y_{100} transition relative luminance then measure the overshoot blur B_O from the peak of the overshoot to the 0% intercept.
- **Undershoot Only $\leq -10\%$:** If the undershoot relative luminance is less than or equal to -10% of the non-blurred y_0-y_{100} transition relative luminance then measure the undershoot blur B_U from the 100% intercept to the minimum of the undershoot.
- **Both Overshoot and Undershoot $\leq \pm 10\%$:** If both the overshoot and undershoot relative luminances are less than or equal to 10% of the non-blurred y_0-y_{100} transition relative luminance then measure the blur B_{OU} from the maximum of the overshoot (peak) to the minimum of the undershoot.
- **Overshoot Over 110 %:** If the overshoot relative luminance exceeds 110% of the non-blurred y_0-y_{100} transition relative luminance then measure the blur B_O from the 110% intersection on the other side of the maximum of the y_0-y_{100} transition relative luminance to the 0% intercept.
- **Undershoot Below -10 %:** If the undershoot relative luminance exceeds 10% of the non-blurred y_0-y_{100} transition relative luminance then measure the blur B_U from the top 100% intercept to the -10% intersection on the other side of the minimum of the $i_{10}-i_{90}$ transition relative luminance.
- **Overshoot Over 110% and Undershoot Below -10% :** If the overshoot and undershoot relative luminances exceed the 110% and -10% levels respectively of the non-blurred y_0-y_{100} transition relative luminance then measure from the 110% intersection on the other side of the maximum to the -10% intersection on the other side of the minimum of the transition.

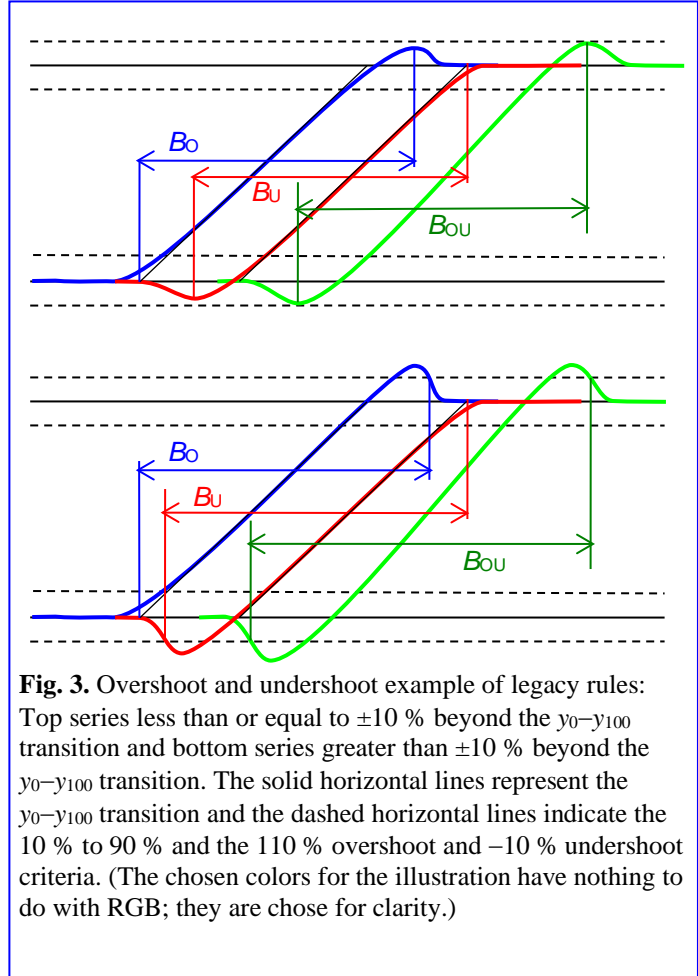


Fig. 3. Overshoot and undershoot example of legacy rules: Top series less than or equal to $\pm 10\%$ beyond the y_0-y_{100} transition and bottom series greater than $\pm 10\%$ beyond the y_0-y_{100} transition. The solid horizontal lines represent the y_0-y_{100} transition and the dashed horizontal lines indicate the 10 % to 90 % and the 110 % overshoot and -10% undershoot criteria. (The chosen colors for the illustration have nothing to do with RGB; they are chose for clarity.)



12.4.2 GAUSSIAN EDGE TIME

DESCRIPTION: We measure the motion blur by fitting a cumulative Gaussian function to the moving-edge temporal profile (METP). We derive the metric Gaussian edge time (GET) from the estimated standard deviation of the Gaussian.

The Gaussian edge time (GET) metric is analogous in expected value to the blurred-edge time (BET) but is a more robust measurement. It does not rely on arbitrary filtering of the waveform or problematic methods of estimating intersections of the waveform with 10% and 90% values. The associated metrics, motion temporal bandwidth (MTB) and motion spatial bandwidth (MSB) are measures of temporal and spatial modulation transfer function (MTF) in the presence of motion blur.

Units: milliseconds (ms) for time, Hz for temporal frequency; and **Symbol:** B_G for Gaussian edge, f for time in frames, R_{start} for beginning relative luminance, R_{end} for ending relative luminance, σ for standard deviation,

μ for Gaussian mean, v for speed in px/frame, w for frame rate in Hz, r for display visual resolution in px/degree.

PROCEDURE:

1. This metric begins with a moving-edge temporal profile (METP) as defined in § 12.2 Moving-Edge Blur Measurement and Analysis. The moving-edge temporal profile (METP) is captured using an appropriate apparatus and method. This standard waveform will consist of a list of relative luminance values at time intervals of τ frames. It results from motion of an edge, between starting and ending gray levels V_{start} and V_{end} , at edge speed v px/frame. The blue points in the figure show an example of METP values. This example exhibits considerable noise.
2. Fit the waveform with a cumulative Gaussian function using a least-squares method. The function has the form:

$$G(f) = R_{\text{start}} + (R_{\text{end}} - R_{\text{start}}) \int_{-\infty}^f \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(t - \mu)^2}{2\sigma^2}\right] dt \quad (1)$$

$$= R_{\text{end}} + \frac{(R_{\text{start}} - R_{\text{end}})}{2} \operatorname{erfc}\left(\frac{f - \mu}{\sigma\sqrt{2}}\right),$$

where R_{start} and R_{end} are starting and ending relative luminance values, f is time in frames, μ is the mean and σ is the standard deviation of the Gaussian in frames, and $\operatorname{erfc}()$ is the complementary error function.

3. (Optional) Truncate the waveform at $\mu \pm 4\sigma$ and repeat the fit. This reduces the influence of noise and drift far from the actual edge. An example waveform is shown in the Fig. 1. The samples (blue dots) are shown as relative luminance versus time in frames. The red curve is the fitted Gaussian. The estimated value of $\sigma = 0.2539$ frames is shown.
4. Compute the Gaussian edge time (GET) in milliseconds from σ in frames and the frame rate w in Hz using the formula

$$B_G = \frac{2563\sigma}{w}. \quad (2)$$

In the example shown in the Figure, GET = 10.846 msec.

5. (Optional) Compute the motion temporal bandwidth (MTB) from the formula

$$W_{\text{MTB}} = \frac{w\sqrt{2\ln 2}}{2\pi\sigma} \quad (3)$$

where σ is in frames and the motion temporal bandwidth (MTB) is in Hz. This is the half-amplitude bandwidth, in Hz of the modulation transfer function (MTF) imposed by motion. In the example shown, $W_{\text{MTB}} = 44.283$ Hz.

6. (Optional) Compute the motion spatial bandwidth (MSB) from the formula

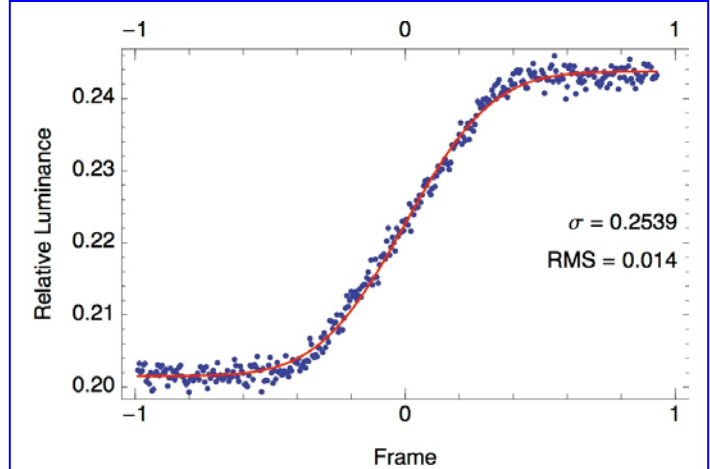


Fig. 1. Example of Gaussian curve (red) fitted to the moving-edge temporal profile (METP) (blue dots) to estimate the Gaussian edge time (GET).



$$W_{\text{MSB}} = \frac{r\sqrt{2\ln 2}}{2\pi\sigma v} = \frac{r}{vw} W_{\text{MTB}}, \quad (4)$$

where r is display visual resolution in px/degree, v is speed in px/frame, and w is the frame rate in Hz. This is the half-amplitude spatial bandwidth, in cycles/degree, of the modulation transfer function (MTF) imposed by motion. In the example shown, if $w = 60$ Hz, and $v = 8$ px/frame, $r = 48$ pixels/deg, $W_{\text{MSB}} = 4.428$ cycles/deg.

COMMENTS: The derivation of motion temporal bandwidth (MTB) and motion spatial bandwidth (MSB) are based on a treatment of the motion blur as a linear filtering process with a Gaussian impulse response and modulation transfer function (MTF). The presence of a nonlinear gamma function and asymmetries between on and off step responses of the display may make these measurements different from bandwidth measured directly, for example using the methods described in § 12.5 Motion Resolution Measurements.



Did you know that
this chapter is not
only about LCDs?

Oh!



12.4.3 VISIBLE MOTION BLUR

DESCRIPTION: The visible motion blur (VMB) metric converts the moving-edge temporal profile (METP) into a measure of the visibility of motion blur in units of just noticeable difference (JND). The METP is a discrete sequence of relative luminances, which we write here as $R(k)$, where k represents an integer sample index, and the time between samples is τ in units of frames. This waveform is a standard physical measurement of motion blur and can be acquired in several ways (§ 12.1.1). It describes the profile of a motion-blurred edge. An example of an METP is shown in Fig. 1.

Symbol: τ for time between samples in frames, Δx for distance between samples in degrees of visual angle, $R(k)$ for the Moving Edge Temporal Profile, v for speed in px/frame, r for display visual resolution in px/degree, J_{mb} for visible motion blur. Unit: JND.

PROCEDURE:

1. Determine the interval between samples Δx in units of degree of visual angle, given by

$$\Delta x = \tau v / r \quad (1)$$

where v is the speed of edge motion in px/frame and r is the visual resolution of the display in px/degree. If plotted against space in degrees, the sequence is now called the moving edge spatial profile (MESP).

2. The sequence $R(k)$ consists of a transition between a starting and an ending relative luminance (R_{start} and R_{end}). Trim the length of sequence to the approximate midpoint of the transition plus and minus $N_\sigma \geq 8$ times the halfwidth of the transition. One convenient means of accomplishing this is by fitting with a cumulative Gaussian, as in § 12.1.6, and trimming to the mean plus and minus N_σ standard deviations. This also provides estimates of the relative luminances R_{start} and R_{end} . It is convenient to make the length of the trimmed sequence an even number K . A picture of a trimmed MESP is shown in Figure 3a.
3. Create three convolution kernels, $H_c(k)$, $H_s(k)$ and $H_m(k)$. Each of these is a discrete sequence obtained by evaluating a kernel function at a discrete set of points. The three sequences are given by

$$H_c(k) = \frac{1}{s_c} \operatorname{sech} \left(\pi \frac{k \Delta x}{s_c} \right), \quad k = -\frac{K}{2} \dots \frac{K}{2} - 1 \quad (2)$$

$$H_s(k) = \frac{1}{s_s} \exp \left[-\pi \left(\frac{k \Delta x}{s_s} \right)^2 \right], \quad k = -\frac{K}{2} \dots \frac{K}{2} - 1 \quad (3)$$

$$H_m(k) = \frac{1}{s_m} \exp \left[-\pi \left(\frac{k \Delta x}{s_m} \right)^2 \right], \quad k = -\frac{K}{2} \dots \frac{K}{2} - 1 \quad (4)$$

These are called the center kernel, the surround kernel, and the masking kernel (Figure 2). These kernels have respective scales of s_c , s_s , and s_m , measured in degrees of visual angle. They are normalized to have an integral of 1. The first two simulate the processing of the luminance waveform by retinal ganglion cells with antagonistic center and surround components. The center component incorporates the blur due to the visual optics, and possibly further early neural pooling, while the surround computes an average of the local luminance and uses it to convert luminance to local contrast.

4. Compute the local contrast $C(k)$ from the relative luminance waveform and the convolution kernels,

$$C(k) = \frac{H_c(k) \otimes R(k)}{\kappa H_s(k) \otimes R(k) + (1 - \kappa) \bar{r}} - 1, \quad (5)$$

where \otimes indicates discrete convolution, κ is a parameter (adaptation weight), and \bar{r} is the average relative luminance and can be estimated as the mean of r_0 and r_1 .

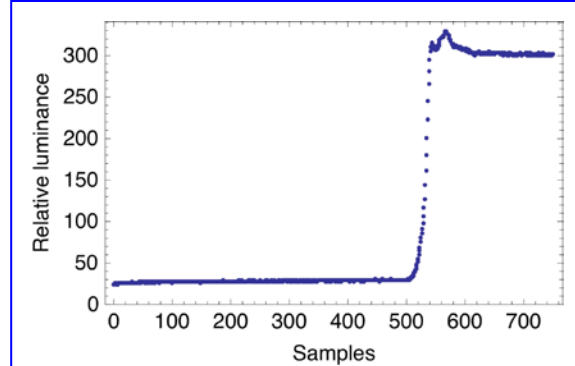


Figure 1. A moving edge temporal profile (METP).

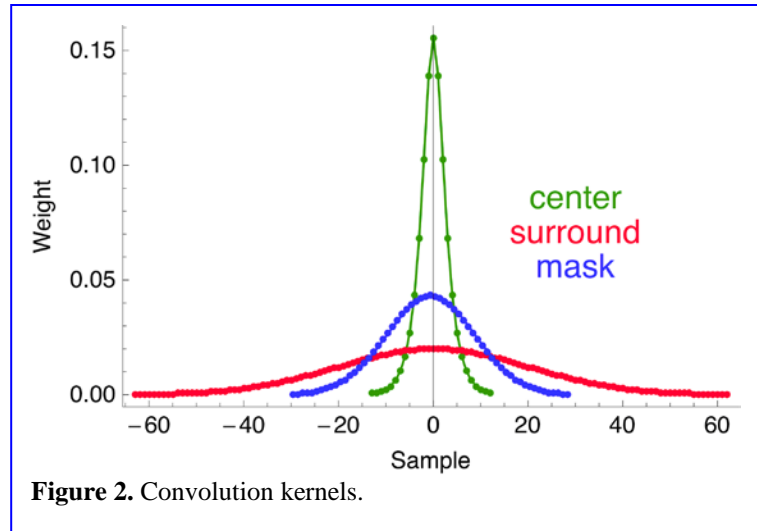


Figure 2. Convolution kernels.

5. Compute the masked local contrast $M(k)$ from the local contrast and the masking kernel H_m ,

$$M(k) = \frac{C(k)}{\sqrt{1 + H_m(k) \otimes [C(k)/T]^2}} \quad (6)$$

where T is a parameter, the masking threshold, with units of contrast.

6. Compute the visibility of the motion blur J_{mb} given by

$$J_{mb} = S \left[\Delta x \sum_k |M_1(k) - M_2(k)|^\beta \right]^{1/\beta} \quad (7)$$

where S and β are parameters. M_1 and M_2 are versions of M from Eq. (6) that are produced by inputs R_1 and R_2 , where R_1 is the actual blurred edge and R_2 is the ideal step edge of the same starting and ending relative luminance. The location of the ideal edge must be adjusted to find the minimum value of J_{mb} (Fig. 3f). Recommended parameters are given in Table 1.

Table 1. VMB Parameters.

sym bol	definition	units	example value
s_c	center scale	degrees	2.77/60
s_s	surround scale	degrees	21.6/60
s_m	masking scale	degrees	10/60
κ	adaptation weight	dimensionless	0.772
T	masking threshold	contrast	0.3
S	sensitivity	dimensionless	217.6
β	pooling exponent	dimensionless	2

REPORTING: In addition to values of J_{mb} , report all parameters used.



COMMENTS: (1) **Illustration:** Illustrations of the steps in the calculation of VMB are shown in Fig. 3. (2) **Veiling luminance:** Where appropriate, a veiling luminance should be included in the waveform. (3) **Patent:** An implementation of this metric is the subject of a NASA patent application.

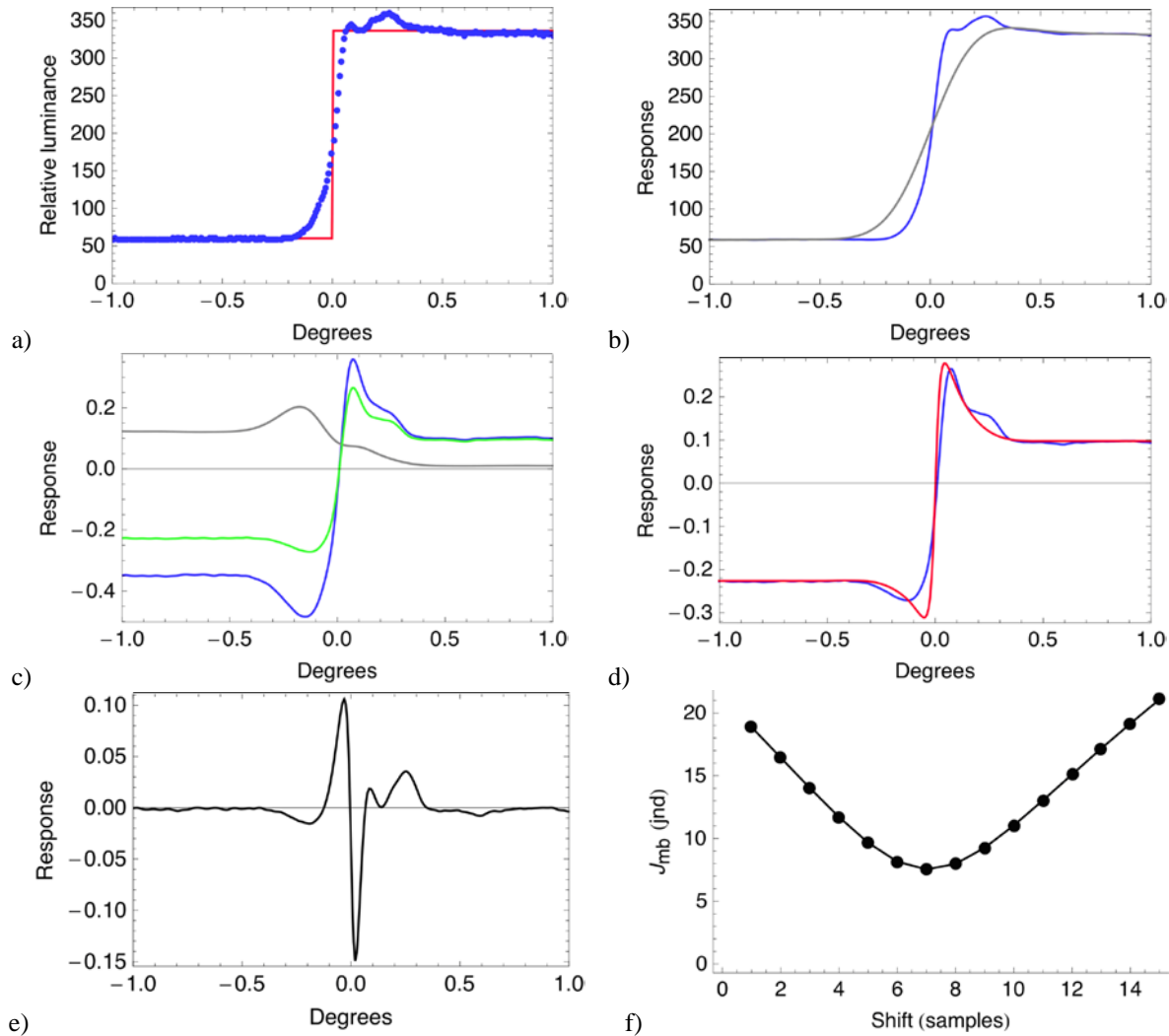


Fig. 3. Visible motion blur (VMB) algorithm. **a)** moving-edge spatial profile (MESP) (blue) and matching ideal edge (red), a veiling relative luminance of 50 has been included, **b)** MESP convolved with center (blue) and surround (gray) kernels, **c)** MESP local contrast (blue), local contrast energy (gray), and masked local contrast (green), **d)** masked local contrast for MESP (blue) and for matching ideal edge (red), **e)** difference of masked local contrasts, **f)** visible motion blur as a function of shift of the ideal edge. Final value of J_{mb} is the minimum of this curve, 7.54 JND. In this example, speed $v = 16$ px/deg, visual resolution $r = 64$ px/degree, sample spacing $\tau = 0.02867$ frames, veiling relative luminance = 50.



12.4.4 COMBINED BLURRED-EDGE TIME

ALIAS: MPRT

DESCRIPTION: When moving-edge-blur measurements are made for multiple gray-gray transitions, there is a question of how to combine them into a single metric. There are many possible combining possibilities, and we enumerate one of them here. We describe these in terms of combining estimates of B_{BET} , the blurred-edge time (BET), but they could also be used to combine multiple estimates of other motion-blur metrics. Unit: ms.

Procedure For each possible procedures, we assume there are multiple measurements: $B_{\text{BET}ij}$, $i = 1, \dots, N$, $j = 1, \dots, N$, where $i \neq j$. Here we provide one example or a combined metric, $[B_{\text{BET}}]_{\text{ave}}$. The measurements are combined using the following rule:

$$[B_{\text{BET}}]_{\text{ave}} = \frac{1}{N(N-1)} \sum_{i=1}^N \sum_{\substack{j=1 \\ j \neq i}}^N B_{\text{BET}ij}.$$

Other quantities of interest are:

$$[B_{\text{BET}}]_{\text{max}} = \max(B_{\text{BET}ij}), \quad i = 1, \dots, N, \quad j = 1, \dots, N, \quad i \neq j.$$

and

$$[B_{\text{BET}}]_{\text{min}} = \min(B_{\text{BET}ij}), \quad i = 1, \dots, N, \quad j = 1, \dots, N, \quad i \neq j.$$

REPORTING

Report the following:

1. The speed of moving edge v px/frame
2. The refresh rate w frames/s.
3. The average $[B_{\text{BET}}]_{\text{ave}}$.
4. The minimum $[B_{\text{BET}}]_{\text{min}}$.
5. The maximum $[B_{\text{BET}}]_{\text{max}}$.
6. Number of gray levels (M).
7. The start gray levels V_{start} and final gray levels V_{end} .

NOTE: If any other combination metrics are reported they must be clearly labeled and clearly defined so that they are not confused with the above average, minimum, and maximum, and so they are not used as a replacement for the above reported values of the average, minimum, and maximum.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting Example

Moving Edge Speed, v (px/frame)	8
Refresh Rate, w (frames/s)	60
$[B_{\text{BET}}]_{\text{ave}}$ (ms)	x.x
$[B_{\text{BET}}]_{\text{min}}$ (ms)	x.x
$[B_{\text{BET}}]_{\text{max}}$ (ms)	x.x
Number of gray levels (M)	9
Start gray level, V_{start}	0
End gray level, V_{end}	255

COMMENTS: Research is underway to evaluate the most appropriate combining rules. “MPRT” originally stood for “motion picture response time,” but later changed to “moving picture response time” or “moving pattern response time,” and was equivalent to our $[B_{\text{BET}}]_{\text{ave}}$.



12.4.5 INTEGRATED ΔE FROM METTP

DESCRIPTION: This metric quantifies the distortion of the previously obtained data as the departure in ΔE from a straight line between the starting and ending colors $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} integrated over time or space. **Symbol:** \mathcal{J} , \mathcal{J}_{deg} . Unit: s, degrees, respectively.

This metric may be useful for a variety of color shifting due to motion. See Comments below.

PROCEDURE: We use the data collected from the previous measurement method, § 12.3.5 Color Moving-Edge Blur, with the additional measurement of the color of white.

1. Obtain the color of white: $\mathbf{C}_W = (X_W, Y_W, Z_W)$.
2. Obtain the data from the previous measurement method giving the starting color $\mathbf{C}_{\text{start}} = (X_{\text{start}}, Y_{\text{start}}, Z_{\text{start}})$, the ending color $\mathbf{C}_{\text{end}} = (X_{\text{end}}, Y_{\text{end}}, Z_{\text{end}})$, and the transition colors $\mathbf{C}_i = (X_i, Y_i, Z_i)$ for $i = 1, 2, 3, \dots, N$, where for $i = 1$ is for $\mathbf{C}_1 = \mathbf{C}_{\text{start}}$ and $i = N$ is for $\mathbf{C}_N = \mathbf{C}_{\text{end}}$. The time interval between data points is Δt in seconds.

ANALYSIS:

1. The color coordinate $\mathbf{T}_i = (X'_i, Y'_i, Z'_i)$ of the point on the line $\mathbf{F} = \mathbf{C}_{\text{end}} - \mathbf{C}_{\text{start}}$ between $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} that is closest to the data point \mathbf{C}_i is given by

$$\mathbf{T}_i = \mathbf{C}_{\text{start}} + [(\mathbf{C}_i - \mathbf{C}_{\text{start}}) \cdot \mathbf{e}] \mathbf{e}, \quad (1)$$

where \mathbf{e} is the unit vector along the line between $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} , given by

$$\mathbf{e} = \mathbf{F}/|\mathbf{F}| = (\mathbf{C}_{\text{end}} - \mathbf{C}_{\text{start}})/|\mathbf{C}_{\text{end}} - \mathbf{C}_{\text{start}}|. \quad (2)$$

In the above, the symbol “ \cdot ” represents the dot product between two vectors giving the projection of one vector upon another and the absolute value “ $|\dots|$ ” gives the magnitude of a vector. In terms of the tristimulus values we have:

$$\mathbf{e} = (e_X, e_Y, e_Z) = \mathbf{F}/|\mathbf{F}| = \left(\frac{X_{\text{end}} - X_{\text{start}}}{F}, \frac{Y_{\text{end}} - Y_{\text{start}}}{F}, \frac{Z_{\text{end}} - Z_{\text{start}}}{F} \right), \quad (3)$$

where F is the magnitude of the vector \mathbf{F} between $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} :

$$F = \sqrt{(X_{\text{end}} - X_{\text{start}})^2 + (Y_{\text{end}} - Y_{\text{start}})^2 + (Z_{\text{end}} - Z_{\text{start}})^2}. \quad (4)$$

The closest colors to the measured colors $\mathbf{C}_i = (X_i, Y_i, Z_i)$ on the line between $\mathbf{C}_{\text{start}}$ and \mathbf{C}_{end} , $\mathbf{T}_i = (X'_i, Y'_i, Z'_i)$, are given by the set of tristimulus components:

$$\mathbf{T}_i = \begin{pmatrix} X'_i \\ Y'_i \\ Z'_i \end{pmatrix} = \begin{pmatrix} X_{\text{start}} + (X_i - X_{\text{start}})(X_{\text{end}} - X_{\text{start}})/F \\ Y_{\text{start}} + (Y_i - Y_{\text{start}})(Y_{\text{end}} - Y_{\text{start}})/F \\ Z_{\text{start}} + (Z_i - Z_{\text{start}})(Z_{\text{end}} - Z_{\text{start}})/F \end{pmatrix}. \quad (5)$$

We now have a set of transitions colors \mathbf{C}_i and their corresponding closest colors \mathbf{T}_i along a line representing a perfect transition.

2. We convert these tristimulus values to CIELUV coordinates to obtain new sets of color representations, $\mathbf{C}_i = (L^*_i, u^*_i, v^*_i)$ and $\mathbf{T}_i = (L^{*'}_i, u^{*'}_i, v^{*'}_i)$. Note that to compute the CIELUV representation we must measure a

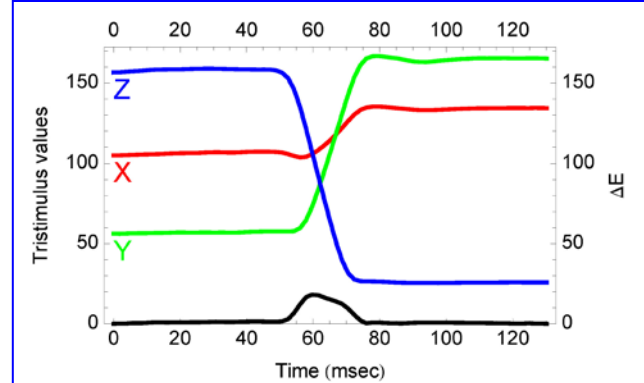


Fig. 1. Example of the moving-edge tristimulus temporal profile (METTP) from the example shown in 12.3.4. The horizontal axis has been converted to msec. The black curve shows the time course of ΔE during the edge transition. The integral of this function is \mathcal{J} .

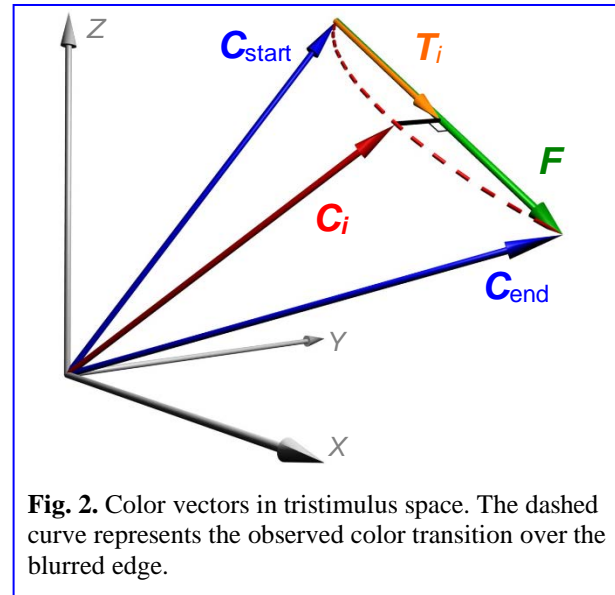


Fig. 2. Color vectors in tristimulus space. The dashed curve represents the observed color transition over the blurred edge.



white point, $\mathbf{C}_W = (X_W, Y_W, Z_W)$. An example of the CIELUV representation of the transition is shown in Fig. 3. See Appendix B1.2 Colorimetry for conversions: As a reminder: $L^* = 116f(Y/Y_W) - 16$, where if $Y/Y_W > (6/29)^3$ then $f(Y/Y_W) = (Y/Y_W)^{1/3}$ else for $Y/Y_W \leq (6/29)^3$ then $f(Y/Y_W) = (841/108) Y/Y_W + 4/29$; $u^* = 13L^*(u' - u'_W)$, $v^* = 13L^*(v' - v'_W)$, where $u' = 4X/(X + 15Y + 3Z)$ and $v' = 9Y/(X + 15Y + 3Z)$.

3. The color differences between these two sets, $i = 1, 2, 3, \dots, N$, are

$$\Delta E_i = \sqrt{(L_i^* - L_i'^*)^2 + (u_i^* - u_i'^*)^2 + (v_i^* - v_i'^*)^2}. \quad (6)$$

4. The final result is the sum of these values, multiplied by the time interval between samples in seconds

$$\mathcal{J} = \Delta t \sum_{i=1}^N \Delta E_i \quad (7)$$

This is an approximation to the time integral of the deviation. The time between data points i is Δt , and the units of \mathcal{J} are seconds.

5. To convert this to a spatial measure in units of angle (degrees) multiply by the speed v in px/frame and the frame rate w in frames/sec, and divide by the display visual resolution r , in px/degree,

$$\mathcal{J}_{\text{deg}} = \frac{vw}{r} \mathcal{J}. \quad (8)$$

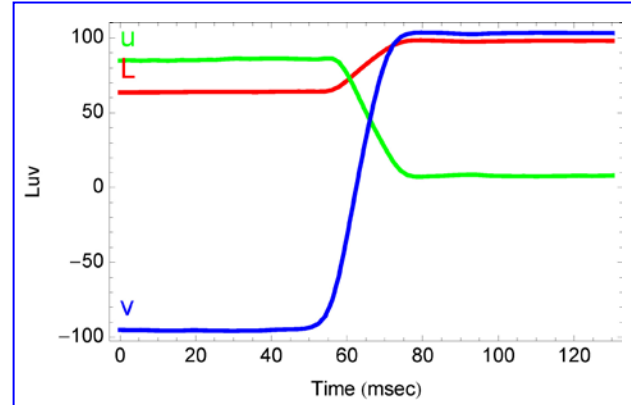


Fig. 3. Example of the moving-edge tristimulus temporal profile (METTP) converted to $L^*u^*v^*$ values.

Units for \mathcal{J}_{deg} are in degrees. For the example shown in Fig. 1 and in § 12.3.5 Color Moving Edge Blur: $\mathcal{J} = 0.344$ s.

Assuming a speed of $v = 8$ px/frame, a frame rate of $w = 60$ Hz (or 60 frames/s), and a visual resolution of $r = 32$ px/degree, we have $\mathcal{J}_{\text{deg}} = 5.16$ degrees.

REPORTING: For each edge tested, report the sampling interval, τ , the frame rate w , the RGB level for the initial color, the final color, the scroll speed v (px/frame), and the visual resolution r (px/deg). For each sample $i = 1, 2, 3, \dots, N$, report X , Y and Z , L^* , u^* , v^* , and ΔE_i . Finally, \mathcal{J} is reported.

—SAMPLE DATA ONLY—									
Do not use any values shown to represent expected results of your measurements.									
Reporting Example:									
$\tau =$	0.005	frames		v (speed)		8	px/frame		
$w =$	60	frames/s		r (visual resolution)		32	px/degree		
$\Delta t =$	83.33...	μs		T (refresh period)		16.66...	ms (=1/w)		
Initial values:	R	G	B	X	Y	Z	L^*	u^*	v^*
White	255	255	255	160.9	174.2	183.3	100.0	0.00	0.00
Initial Color	255	0	255	104.9	56.12	156.7	63.52	84.81	-95.13
Final Color	255	255	0	134.5	165.3	25.81	97.99	7.996	103.25
Profile Data									
Sample #	Time [ms]	X	Y	Z	L^*	u^*	v^*	ΔE	
1	0	104.9	56.12	156.7	63.52	84.81	-95.13	0	
...									
34	10.85	105.7	72.97	107.0	70.79	77.57	-36.82	18.15	
...									
73	130.2	134.5	165.3	25.81	97.99	7.996	103.25	0	
								\mathcal{J}	0.344 s
								\mathcal{J}_{deg}	5.16 °

COMMENTS: This metric can be used for grayscale aberrations, color aberrations and color break up.



12.5 MOTION RESOLUTION MEASUREMENTS

Motion blur can also be measured by examining the reduction in the amplitude of sinusoidal grating as it is moved across the display and viewed by a pursuit camera or similar apparatus. Because this measurement constitutes a spatial modulation transfer function (MTF) at various speeds, it is sometimes called the dynamic MTF (DMTF). Because moving edge blur and the dynamic MTF result from the same process (pursuit eye movements and a persistent image) we would expect a relation between them, and that relation is described, at least theoretically, in § 12.5.2 Dynamic MTF. In this section we present two methods to measure motion resolution.



12.5.1 MOVING-PICTURE RESOLUTION

DESCRIPTION: Determine the limiting resolution by capturing images scrolled on the sample display, using a pursuit camera. A set of four-cycled sinusoidal burst patterns having steps of spatial frequencies should be used as a test chart. Limiting resolution is the maximum spatial frequency up to which the modulation transfer function (MTF) is greater than or equal to 5%, maintaining valid four-line shape without severe shifting in phase.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

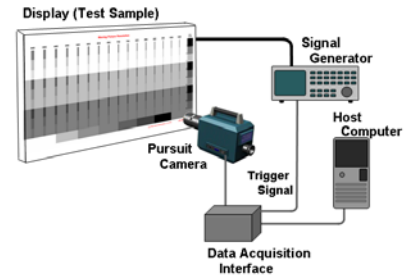
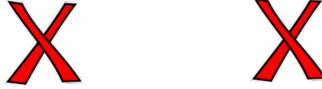


Fig.1. Moving Picture Resolution measurement system.

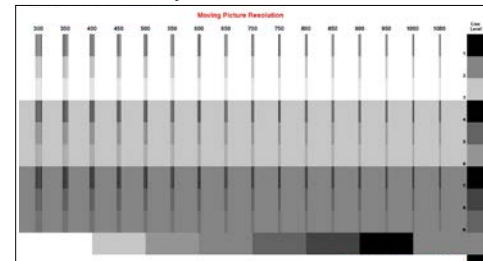


Fig.2. Test Chart

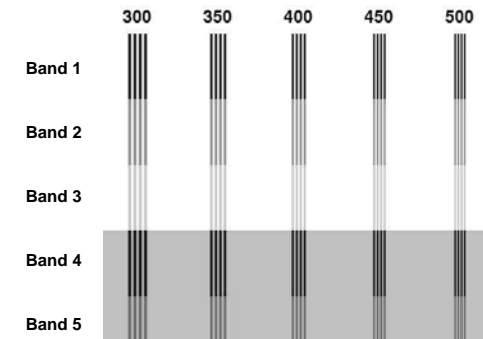


Fig.3. Close-up of Fig 2.

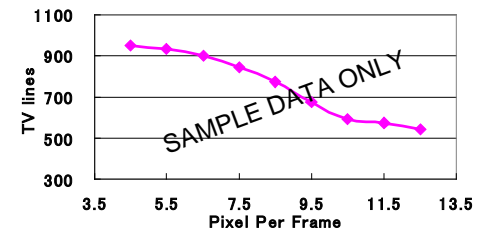


Fig. 4. Sample data.



OTHER SETUP CONDITIONS: The chart consists of four-cycled sinusoidal burst patterns with frequencies extending over the anticipated range of the display. In this example the sample frequencies are from 300 to 1080 tv lines ($5/18$ to $1/2$ cycle/pixel). Suggested step size is 50 lines of resolution for 1080i/p (interlaced or progressive) format, or 5% of full scale for an effective and reliable measurement.

Each pattern should be repeated at three different amplitudes and three different background levels, as shown in Fig. 2 and Fig.3. In this example the background levels are: 255, 192, 128, top to bottom. Target line levels for each background



before sampling are approximately 0%, 50%, and 75% of the background gray level without gamma, that is, using 8-bit gray levels: 0, 128, 192, 0, 96, 144, 0, 64, and 96.

The signal generator requires a sub-sampling functionality, which is realized by outputting the contents of two frame buffers alternately and shifting the pixel position in every two frames.

Disabling over-scan or “dot by dot” setting is required; that is, there must be a one-to-one correspondence with the signal pixels and the display pixels. Dithering and frame rate control (FRC) are the common driving schemes to generate grayscale in displays, by tuning pixels on and off over several frame periods. To average out of the possible effects from FRC or dithering used in displays, 1/15 sec shutter is normally used. For 60Hz system, this means averaging of four frames. It is long enough to neglect FRC. Be sure that the exposure (shutter time) is an integral number of frames.

PROCEDURE:

1. Scroll the test chart as shown in Fig. 2, with an appropriate scrolling speed.
2. Capture each part of sinusoidal pattern by synchronizing the movement of the pursuit camera.
3. Average each sinusoidal pattern over rows to produce a one-dimensional waveform.
4. Determine the modulation amplitude for each sinusoidal pattern. Modulation amplitude is determined from the level of fundamental component from a Fourier transform of the waveform. A plot of the amplitude versus frequency is the modulation transfer function (MTF).
5. Analyze the MTF to determine the limiting resolution for each band, defined as the amplitude larger than or equal to 5%. Interpolation should be used between sample frequencies.
6. Repeat the process for three different contrasts and three different background levels.
7. Repeat the above procedure for the different scrolling speeds.

ANALYSIS: Different schemes may be used to combine the nine limiting resolutions for each scroll speed. The default is to average the nine values.

REPORTING: Report limiting resolutions for each band and calculate the average for all bands as shown in the Table 1. Report limiting resolution for each for each scrolling speed as Table 2 to plot Fig. 4. Also report background levels and target line levels.

COMMENTS: (1) Additional evaluation on shape distortion and phase shifting should be applied depending on the distortion of the waveform. Described above is a basic procedure for automated judgment that should work fine for typical LCD or PDP. However, to cope with displays with irregular response, and to enhance robustness, it is preferable to perform some kinds of waveform check. Examples are symmetry check, phase-shift check, and so on. (2) Response of the FPD generally has level dependencies, depending on the start and target levels. Three backgrounds and three contrasts make nine combinations for a minimum check. (3) The patterns are sinusoidal in grayscale, rather than in luminance, so depending upon the gamma, the captured waveform may not be sinusoidal. However, this distortion is considered acceptable.

Speaking, I'm sure, for the committee: It is with great reluctance that we see and agree with your logic.



JOE WINS ONE!



12.5.2 DYNAMIC MTF

ALIAS: spatiotemporal contrast degradation

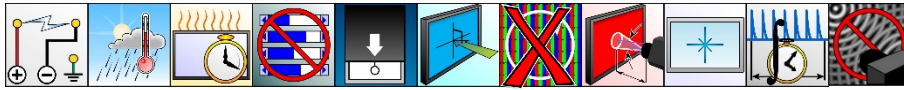
DESCRIPTION: We measure the temporal response of the display with temporally modulated full-screen patterns and use a spatiotemporal integration model to simulate smooth-pursuit eye-tracking and light integration at the human retina. From these data a dynamic modulation transfer function (DMTF) is determined to characterize the contrast attenuation of a display when rendering a moving pattern at different spatial frequency components for specific motion speeds, as shown in Fig. 1.

Units: None. **Symbol:** M_{DMTF} .

Consider a stationary sinusoidal luminance pattern on the display screen. Assume that the pattern moves with a specific speed from left to right over the display surface, but at the same time the eye is perfectly following this motion with smooth-pursuit eye tracking. The pattern will be projected as a still image on the retina, but with a possible reduced amplitude because of any blurring. The relative change in amplitude is a measure for the temporal display behavior, which we express as the dynamic modulation transfer function (DMTF), M_{DMTF} . However, this measurement method simulates the smooth-pursuit eye tracking by making a set of temporal response measurements with corresponding temporally modulated full-screen patterns.

We simulate the contrast attenuation of a display at different spatial frequency components for specific motion speeds as follows: The calculation of dynamic modulation transfer function (DMTF) is based on the captured temporal luminance variation for special full-screen input code sequences, which represent the gray-level transitions that will occur when a sinusoidal pattern will move with a specific motion speed. Several sequences with the specific order of full-screen gray levels need to be generated to enable capturing the temporal display behavior with a fast-response luminance sensor. These recorded temporal characteristics translate under the specific condition of smooth-pursuit eye tracking to spatial effects. The spatiotemporal conversion is obtained by assuming smooth-pursuit eye tracking and temporal light integration at the human retina. By modeling this temporal equivalent of a perceived performance of a moving sine wave pattern on the display and calculating the subsequent contrast degradation the dynamic modulation transfer function (DMTF) property is derived.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The display area to be measured shall be as small as possible, which can be achieved by positioning the fast-response luminance detector as close to the display surface as possible. The sampling rate of the luminance detector signal shall be at least 100 samples per frame period.

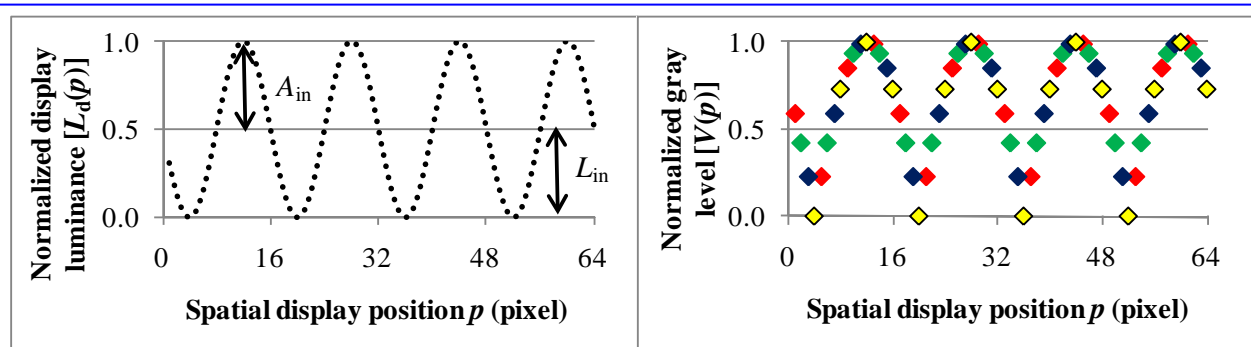


Fig. 2. Reference Pattern used to create the test sequences. The target sinusoidal luminance pattern with $s = 1/16$ cpp (left) and the corresponding gray level values (right), where pixels have been grouped for different test sequences depending on the motion speed. $v = 4$ is assumed in this figure.

PROCEDURE: Note that the display exhibits a refresh rate of w in Hz or in frames per second.



1. **Definition of the reference pattern:** Select an average display luminance L_{in} , a luminance modulation amplitude A_{in} , and a spatial frequency s in cycles/pixel (cpp); see Fig. 2 (left) for an example of the normalized display luminance $L_d(p)$ at position p with a spatial frequency $s = 1/16$ cpp and with the corresponding gray level values $V(p)$ to generate these luminance values. Because of periodicity, the spatial frequency pattern can have multiple periods, with period $1/s$, as demonstrated in Fig. 2 (right). The subsequent gray level sequences for measurement are selected among the gray level values of $V(p)$.
2. **Definition of the motion speed:** Assume the reference pattern $V(p)$ is moving horizontally on the screen with a speed of v in pixel/frame (ppf), such that $1/(vs)$ is number of frames per sequence that results in an integer value. In the ideal case, v is also the speed of smooth pursuit eye tracking, which results in a perceived still image on the human retina.
3. **Definition of the temporally modulated gray level sequence for measurement:** Create a set of $N = v$ (N is numerically equal to v but is unitless) discrete gray level sequences $V_i(f)$ from $V(p)$, where f is a frame index, $f = 1, 2, \dots, 1/(vs)$, in the sequence that refers to a specific position p in the stationary sinusoidal luminance pattern $V(p)$. $V_i(f)$ is the sequence with full-screen gray levels and $i = 1, 2, \dots, N$ is an index that permits N different patterns of the same spatial frequency s to be used with slightly different phases. Each sequence $V_i(f)$ consists of $1/(vs)$ full-screen gray levels, which relation to pixel position p is determined by index i and the motion direction (left to right or right to left). For the example in Fig. 2–right there are 16 pixels in one cycle ($s = 1/16$ cpp). When the pattern would move with a speed v of 4 ppf from left to right, there are only $N = 4$ discrete gray-level transition sequences to be measured to capture the display-induced temporal variations: yellow, blue, green, and red. These are indicated in Fig. 3–left. You will note the different phases in the four $i = 1, 2, 3, 4$ gray level input sequences. Because the motion is from left to right, the corresponding order of the gray levels in the sequence is from right to left. Due to periodicity, in principle, only four transitions per sequence $V_i(f)$ are required to be measured. However, for calculation purposes, the sequence $V_i(f)$ can be extended to include multiple periods. In the example of Fig. 2–right, four periods have been selected.
4. **Temporal response measurements:** With a fast response luminance detector, measure the temporal luminance waveform $L_i(t)$, produced by each sequence $i = 1, 2, \dots, N$ of full-screen gray level sequences $V_i(f)$; see Fig. 3–right for an example for $v = 4$ ppf and $s = 1/16$ cpp.
5. **The spatio-temporal conversion:** The temporal luminance variations of the moving sinusoidal pattern translate to spatial variations in the perceived (retinal) pattern under the assumption of smooth pursuit eye tracking. The resulting perceived luminance profile $L_r(p)$ where p denotes a position index, can be calculated via Eq. (1); see Fig. 4 for an example.
6. **Calculation of DMTF value:** Determine the amplitude A_r of the retinal luminance profile from the plot (Fig. 4) or via Eq. (1). Compute M_{DMTF} via Eq. (2).



7. Repeat steps 2-6 for various speeds v .
8. Repeat steps 1-7 for various spatial frequencies s .

ANALYSIS: Assuming smooth-pursuit eye tracking equivalent to temporal light integration at the retina, then the equivalent retinal luminance in terms of display pixel index p is

$$L_T(p) = w \sum_{i=1}^N \int_{(p-i)/(wN)}^{(p-i+1)/(wN)} L_i(-t) dt. \quad (1)$$

The amplitude A_r can be derived when plotting the result of Eq. (1), with $A_r = [\max(L_r) - \min(L_r)]/2$. For each combination of motion speed v and spatial frequency s , the ratio between the retinal luminance amplitude A_r and the input luminance amplitude A_{in} is defined as:

$$M_{DMTF} = A_r / A_{in}. \quad (2)$$

Dynamic modulation transfer function, representing the spatial frequency response and specifying the spatial information resolving power for display at a certain motion speed. Fig. 1 shows a measurement summary of the results as an example.

REPORTING: Typically, both the average luminance L_{in} and the amplitude A_{in} of the sinusoidal luminance pattern are half the display's peak luminance. The spatial frequency (s) shall range between 0 and 0.5 cpp, and for the motion speed v , values of 2, 4, 8, and 16 ppf shall be selected. The measured dynamic modulation transfer function M_{DMTF} values shall be reported in no more than three significant figures for all measured conditions. Additionally, the M_{DMTF} could be presented in two-dimensional plots. The value of the dynamic modulation transfer function is defined to be one, $M_{DMTF} = 1$, at $s = 0$.

COMMENTS: Determination of the desired input gray scale sequence: Consider a one-dimensional sinusoidal pattern $L_d(p)$ in the luminance domain as shown in Fig. 2. For this pattern, $V_i(f)$ represents the corresponding gray level of pixel p , where $p \in \{1, 2, \dots, N_H\}$, N_H is the number of horizontal pixels of the display, and i is the index representing possible different phases of the sinusoidal pattern. The luminance amplitude of the sinusoidal test pattern is recorded as A_{in} .

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Analysis Example					
Pattern input parameters				Measured parameters	
L_{in} (cd/m ²)	A_{in} (cd/m ²)	w (cpp)	v (ppf)	A_r (cd/m ²)	DMTF
100	100	0.03125	2	98	0.98
			4	94	0.94
			8	77	0.77
			16	44	0.44
100	100	0.0625	2	95	0.95
			4	76	0.76
			8	43	0.43
			16	0	0.0
100	100	0.125	2	75	0.75
			4	43	0.43
			8	0	0.0
			16	0	0.0
100	100	0.25	2	40	0.40
			4	0	0.0
			8	0	0.0
			16	0	0.0

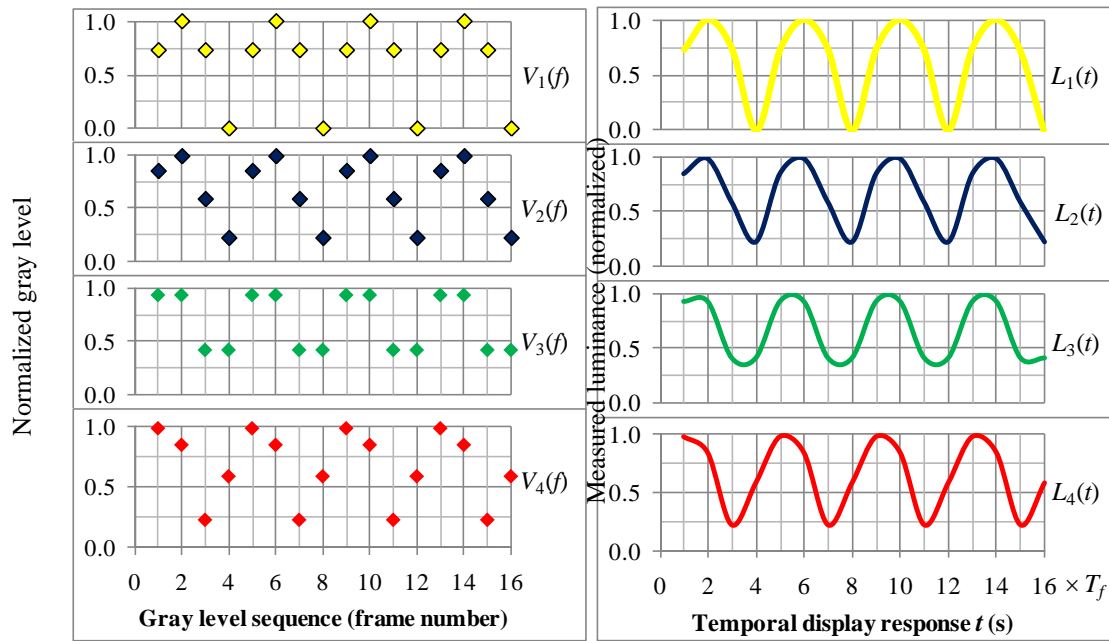


Figure 3. Left side: The gray level sequences for temporal response measurement representing motion of the pattern (Fig. 2–right) from left to right with a speed $v = 4$ ppf. Right side: an example of the correspondingly measured temporal luminance transitions. The left graphs indicate the normalized gray level for each successive frame, where the right graphs indicate the measured (normalized) luminance variation with time, as a consequence of the input sequences. For the right graphs, the numbers on the x-axis correspond to the frame numbers in the input sequence. Therefore, the x-axis shall be multiplied with the frame time ($T_f = 1/w$) to convert to frames.

Assuming that a sinusoidal pattern is scrolling across the screen from left to right, there are only a discrete number of luminance transitions within each pixel, depending on the pattern's spatial frequency and motion speed. For example, when we consider a scrolling sinusoidal pattern (as in Fig. 2), with a spatial frequency of $s = 1/16$ cycles per pixel (cpp), and a speed of $v = 4$ pixels per frame (ppf), because of periodicity only four discrete input code sequences $V_i(f)$ must be measured to capture the different luminance transitions that will occur during this motion. These sequences are indicated with four different colors in Fig. 3–left, where the corresponding temporal luminance transitions are shown in Fig. 3 (right). The recorded temporal luminance transitions serve as input for Eq. 1.

More information on the theoretical background of the DMTF method can be found in: Yuning Zhang, Kees Teunissen, Wen Song, and Xiaohua Li, “Dynamic modulation transfer function: a method to characterize the temporal performance of liquid-crystal displays,” March 15, 2008, Vol. 33, No. 6, Optics Letters, pp. 533 – 535.

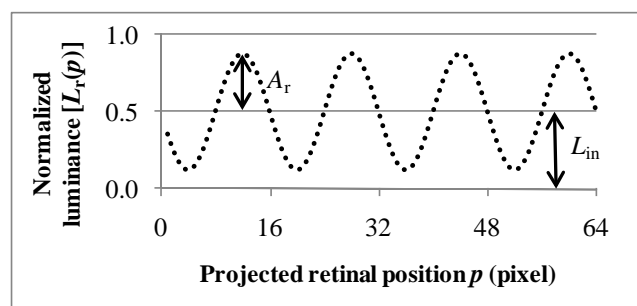


Fig. 4. Example of the perceived luminance L_r during smooth pursuit eye-movements for $s = 1/16$ cpp and $v = 4$ ppf.



12.6 WIREFRAME FLICKERING MEASUREMENT

DESCRIPTION: As fine vertical lines move slowly on an LCD screen, there can be brightening and darkening of pixels. If the rising (brightening) responses are slower than falling (darkening) ones, the overall luminance from the screen has luminance fluctuations, which can be perceived as flicker.

We use a vertical stripe pattern moving at a slow scrolling speed to measure the wireframe flickering (WFF). Measure intensity as a function of time and then use a Fourier analysis to compute flicker intensity as a function of frequency weighted by EIAJ flicker sensitivity (Fig. 2). After calculating flicker levels, report the frequency and flicker level of the highest flicker peak.

Units: Hz, dB

SETUP: Defined by these icons, standard setup details apply (§ 3.2).

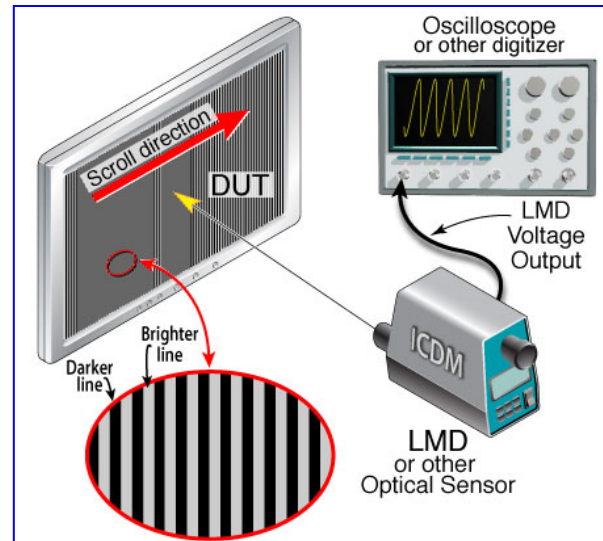
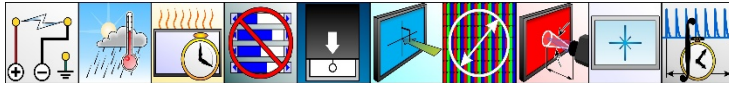


Fig. 1. Schematic diagram of the measurement setup with a detailed view of the vertical stripe pattern used for the measurement.



OTHER SETUP CONDITIONS: **Equipment:** A video generator to produce slow moving alternating pixel vertical lines, an LMD to measure the time-varying luminance, an oscilloscope to record and display the output signal. The LMD must not saturate at the peak of the luminance profile (check this out by removing the filter and looking at the output of the LMD directly).

Test Pattern: Use the scrolling vertical stripe pattern to measure the Wireframe Flicker as shown in Fig. 1. All vertical lines have one-pixel width. When the pattern moves slowly [slower than 1 pixel per frame (ppf)] in a horizontal direction, brighter lines become darker and darker lines brighter at the same time. The speed of $1/m$ ppf means that a pattern stays m -frame times after shifting by 1 pixel. m is an integer and it should be larger than 1. Thus, $1/m$ ppf does not mean a smooth motion. We can measure luminance fluctuation on the LCD screen by moving the vertical stripe pattern with a speed of $1/m$ ppf.

PROCEDURE:

1. Determine the flicker pattern levels. Select the gray levels to produce brightening and darkening pixels. Then select the frame rate which stays m -frame time after the pattern moves by 1 pixel.
2. Collect the intensity data from the LMD for the scrolling pattern.
3. Calculate the fast Fourier Transform (FFT) coefficients and the corresponding flicker levels from the data. The function FFT is defined as equation (1).

$$X(k) = \sum_{n=0}^{N-1} x(n) \cdot \exp(-j2\pi \frac{k}{N} n) \quad (1)$$

$$(k = 0, 1, \dots, N-1)$$

where N is the number of data points and $x(n)$ is measurement data in the time domain. $X(k)$ are the results of the FFT coefficients in the frequency domain. One frequency step of the FFT is equal to sampling frequency (f_s) divided by N (f_s/N).

Table 1. Flicker Weighting Factors		
Use linear interpolation between the listed frequencies. “Scaling: dB” is equivalent to “Scaling: Factor”		
Frequency: Hz	Scaling: dB	Scaling: Factor
≤ 20	0	1.0
30	-3	0.708
40	-6	0.501
50	-12	0.251
> 60	-40	0.010

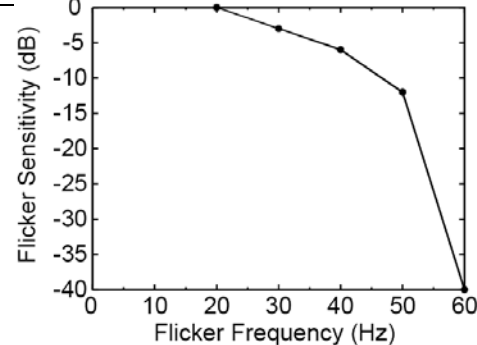


Fig. 2. Flicker sensitivity vs. frequency.



- Plot the FFT coefficient in the frequency domain. Find the FFT coefficients according to frequency from specific peaks. The resulting FFT coefficients are weighted by (multiplied by) the scaling factor corresponding frequency in the table 1. This weighting is performed to adjust the measured flicker levels to match the approximate temporal flicker sensitivity of the human eyes, where flicker sensitivity decreases as the flicker frequency increases.

ANALYSIS:

- Calculate the FFT coefficients. Note that the FFT coefficient for 0 Hz (f_0) is the DC, or average, intensity
- Find the FFT coefficients according to the frequency from specific peaks. Resulting FFT coefficients are weighted (multiplied) by the scaling factor corresponding to frequency in Table 1. If there isn't a scaling factor in Table 1, use linear interpolation between the listed values. The scaled FFT coefficient array can be obtained by the human visual sensitivity factors.
- For each element in the scaled FFT coefficient array, calculate the flicker level using equation (2)

$$\text{flicker level(dB)} = 20\log_{10} \left\{ 2 \times \left[\frac{\text{Weighted}(f_p) \times \text{FFT}(f_p)}{\text{Weighted}(f_0) \times \text{FFT}(f_0)} \right] \right\} \quad (2)$$

$$(\text{main frequency} = f_p = \frac{f_R}{m})$$

where f_R is the panel's refresh rate, f_0 is the DC value of the FFT at 0 or DC, and f_p is the main or primary (most dominant) Fourier component. Therefore, the main or fundamental frequency (f_p) is determined by the pattern scrolling speed, $1/m$ ppf, multiplied by the panel refresh rate. (This is the equation for calculating dB directly from the validated FFT coefficients. If the flicker level is to be calculated from "power spectrum" FFT coefficients, where each coefficient has been squared, EITHER take the square root of each coefficient to yield the validated form, OR use the alternate equation flicker level = $10\log_{10}(\text{power}[n]/\text{power}[0])$ dB. Here, we are calculating the weighted flicker level at each frequency in decibels with respect to the mean luminance.

REPORTING: Report any variations from standard setup/test pattern, $F_{\text{repetition}}$, F_{sample} , and the frequency and value of the largest flicker level. Optionally, report all flicker levels.

COMMENTS: This measurement is intended to be consistent with § 5.13 Flicker in EIAJ ED-2522. Note that the flicker weighting factors shown are from the EIAJ document. Other weighting factors may be used, as long as all interested parties agree and the alternate factors are clearly reported in all documentation.

The cause of WFF is the asymmetric characteristics of rising (or brightening) and falling (or darkening) responses. Thus, there will be brightening and darkening pixels at the same time. The luminance fluctuation should be periodic to simplify the measurement and analysis.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Table 2. Sample Data					
Scroll Rate (pixels/frame)	Magnitude		Main FFT frequency (f_p)	Weight factor	Flicker level
	DC	AC _{main}			
1/2	745.80	80.39	30.27	0.708	-16.32
1/3	825.45	72.67	20.51	1.000	-15.09
1/4	870.89	90.68	14.65	1.000	-13.63
1/5	898.57	64.24	11.72	1.000	-16.89



13. PHYSICAL & MECHANICAL MEASUREMENTS

Mechanical and physical characteristics include size of the display surface, overall dimensions of the display, mounting specifications, mass (or weight), and strength.



13.1 DISPLAY SIZE

Before there were fixed pixel displays, CRTs were the dominant display technology. CRTs have a scanned raster that can vary in position and size as a function of electrical and/or magnetic processing of a scanning electron beam. The number of pixels can also vary as a function of the rate of modulation of the electron beam across each scan line. Thus, the variability in the raster-scanned technology provided a great deal of variability for the size of a raster. Trying to establish a single diagonal value for a CRT raster that could vary significantly lead to some confusion over what the real diagonal size of the CRT display actually was. For a fixed pixel display, the pixels exist physically on a display substrate and can never vary, in size, position, or quantity. That makes it possible to establish guidelines to assure that no significant errors in expressing the diagonal size of fixed pixel displays can ever exist. If the proper guidelines are established and followed, the diagonal number can be a figure of merit for display size that is meaningful and unambiguous. Potential errors for diagonal size varying from the real pixel array diagonal are few, such as error in the exact size is due to rounding, or not addressing all pixels.

There are a number of variables that relate to the sizes associated with the measurement of a FPD. We provide a list here of all the variables used in this section of the document. Many displays made have square pixels. We provide equations for both square and non-square pixels. We summarize the relationships between these variables that may be of use in Table 3 in the next section (13.1.1).

Table of Variables Related to Size	
P_H, P_V, P	Pixel pitch for horizontal, vertical, and for square pixels for which $P_H = P_V = P$, expressed in units of distance per pixel (nm/pixel, mm/pixel, in/pixel, ...)
N_H, N_V	Number of pixels in the horizontal and vertical direction (no units)
S_H, S_V, S	Pixel spatial frequency for horizontal, vertical, and for square pixels ($S = 1/P$), expressed in units of number of pixels per unit distance (pixels/mm, pixels/cm, pixels/in, ...)
D	Diagonal measure of the screen, expressed in units of distance (mm, cm, m, in, ...)
H, V	Horizontal and vertical measure of the screen displayable area (total area of all addressable pixels), expressed in units of distance (mm, cm, m, in, ...)
α	Aspect ratio $\alpha = H/V$ (no units)
A	Area of viewable display surface ($A = HV$)
a	Rectangular area allocated to each pixel ($a = P_H P_V$)

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



13.1.1 SIZE OF VIEWABLE AREA

In the following it is assumed that we are referring to a fixed rectangular array of pixels used to produce information. The size of the viewable area includes only that part of the display surface which can be seen by the user of the display under normal operating conditions. Any pixels behind a bezel are not to be included. Any border that doesn't contain information-producing pixels is also not included in the viewable area. Thus, the viewable area is that group of pixels that contribute to the display of information and can be controlled. See Fig. 1. For most displays you will always know the number of horizontal pixels (or columns) N_H and the number of vertical pixels N_V .

In all that follows reference is made to several measured dimensions. Should you desire to measure any of these sizes, caution is in order. **Using a ruler placed over the display may damage the surface of the display.** Further, many inexpensive rulers may not be sufficiently accurate for use, e.g., we

have seen some inexpensive rulers exhibit errors of ± 1 mm over a 30 mm distance. When a ruler is used, there can be a parallax error because the surface upon which the ruler is placed can be separated from the pixel surface by usually a covering glass or plastic, and unless the eye is carefully placed along a perpendicular line from the surface over the measurement point, an error may occur because of the position of the eye. A traveling microscope or equivalent is best suited for these types of measurements.

PIXEL FORMAT ($N_H \times N_V$): The viewable or displayed surface of a DUT comprises a rectangular array of pixels specified by having a number N_H of pixels in the horizontal direction (number of columns) and a number N_V of pixels in the vertical direction (number of rows or lines). The product of the horizontal and vertical number of pixels

$$N_T = N_H \times N_V, \quad [\text{total number of pixels}] \quad (1)$$

is the total number of pixels N_T in the DUT.

HORIZONTAL SIZE, VERTICAL SIZE, AND AREA (H, V, A): The horizontal size H is the distance from the left-most part of the active pixel on the left side of any line to the right-most part of the active pixel on the right side of the same line. The product

$$A = HV. \quad [\text{area}] \quad (2)$$

is the size of the viewable area. See Fig. 1.

PIXEL PITCH AND SPATIAL FREQUENCY (P_H, P_V, P, S_H, S_V, S):

The horizontal distance between a point on one pixel to the similar point on the next horizontal pixel is the horizontal pixel pitch P_H . Similarly, the vertical pitch P_V is the vertical distance between two similar points on adjacent vertical pixels. In Fig. 1, upper right inset showing an arbitrary RGB rectangular subpixel configuration, the pixel pitch is depicted as being measured from the upper left corner of the green subpixel to the upper left corner of the adjacent green subpixel. For square pixels

$$\text{pixel pitch:} \quad P_H = P_V = P. \quad [\text{for square pixels only}] \quad (3)$$

Associated with the pixel pitch is the spatial frequency of the pixels, often called by units such as “pixels per centimeter” or “pixels per inch.” The spatial frequency is inversely related to the pitch

$$\text{spatial frequency:} \quad S_H = 1/P_H, \quad S_V = 1/P_V, \quad (4a)$$

$$S = 1/P. \quad [\text{for square pixels only}] \quad (4b)$$

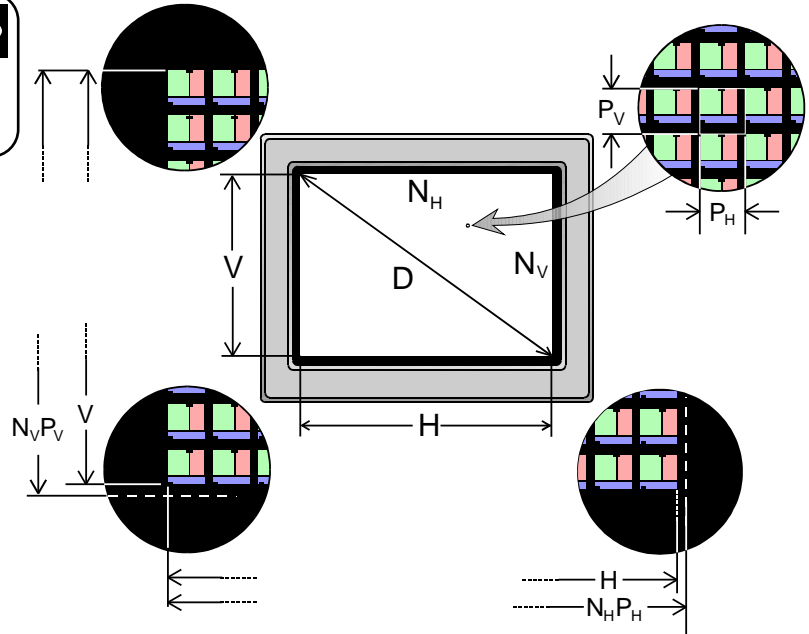


Fig. 1. Dimensional measurements of fixed-array display with arbitrary pixel arrangement (as an example).



Some use the term “dots per ...” for “pixels per ...” whereas dot most often refers to the subpixel, usage has been sloppy, and you are warned to be cautious in interpreting to what spatial frequency reference is being made when the term “dot” is used.

Given that the display has N_H horizontal pixels (or columns) and N_V vertical pixels (rows or lines) we might be tempted to claim that the size of either the horizontal or the vertical dimension of the display is simply the product of the number of pixels and the pitch in that direction. This is not exactly true, but the error is generally so small that it can be ignored—for typical desktop or laptop display applications, for example, the difference will be on the order of 100 μm . The lower two insets in Fig. 1 show how the actual display horizontal and vertical dimensions are slightly smaller than the number of pixels times the pixel pitch. If the pixel had a 100 % fill factor, then the following equations would be exact. (The pixels shown in Fig. 1 have a 52 % fill factor.)

horizontal, vertical size: $H \cong N_H P_H$, $V \cong N_V P_V$; [all pixels] (5a)

$$H \cong N_H P, \quad V \cong N_V P. \quad [\text{for square pixels only}] \quad (5b)$$

NOTE: We will generally treat and write these approximations as exact equalities in what follows with the understanding that, should the error be important, all interested parties will be made aware of the slight difference.

AREA ALLOCATED TO A RECTANGULAR PIXEL (a): The rectangular matrix of pixels has a certain area associated with the containment of each pixel. The area a allocated to each pixel is simply the product of the horizontal and vertical pixel pitches

area allocated to pixel: $a = P_H P_V$, [all pixels] (6a)

$$a = P^2. \quad [\text{for square pixels only}] \quad (6b)$$

See Pixel Fill Factor measurement (§ 7.4) for determining the fraction of a that is a pixel.

DIAGONAL SIZE: To describe the size of a display surface the diagonal size is presently the most common metric for specifying the viewable size of a display. The diagonal measure shall refer to only the part of the display surface that has visible pixels that can be controlled to display information.

$$\text{diagonal:} \quad D = \sqrt{H^2 + V^2}. \quad [\text{exact}] \quad (7)$$

There are several ways to express or calculate the diagonal depending upon what information is available. Should the pixel pitch and the number of pixels be the most reliable information, then

$$D = \sqrt{(P_H N_H)^2 + (P_V N_V)^2}, \quad [\text{all pixels}] \quad (8a)$$

$$D = P \sqrt{N_H^2 + N_V^2}. \quad [\text{for square pixels only}] \quad (8b)$$

If the pixel spatial frequency are known accurately, we can use

$$D = \sqrt{\left(\frac{N_H}{S_H}\right)^2 + \left(\frac{N_V}{S_V}\right)^2}, \quad [\text{all pixels}] \quad (9a)$$

$$D = \sqrt{N_H^2 + N_V^2} / S. \quad [\text{for square pixels only}] \quad (9b)$$

Caution should be exercised in assessing the uncertainty of the spatial frequency or, e.g., “dots per inch” (DPI). In general industry use, the spatial frequency (DPI) is often rounded to whole numbers and therefore may not be accurately reported.

We recommend that the diagonal measurement be reported within ± 0.5 % of its true value (this includes all measurement error as well as rounding). For example, with displays used in an office or laptop environment, this recommendation amounts to requiring that the diagonal be expressed to at least the nearest 1.3 mm (± 0.5 mm) or the nearest 1/10 in (± 0.05 in). For calculation purposes a more precise diagonal measurement may be desired. **Note: Although rounding to no coarser than ± 0.5 % of the diagonal’s size is recommended, it is always acceptable to express the diagonal to a greater precision. Expressing the diagonal with a lower precision than ± 0.5 % is not acceptable.** Examples of the worst-case errors are shown in Table 1.

Table 1. Examples of Worst-Case Error		
Actual Diagonal	Reported Diagonal	Error
306.045...mm (12.049...in)	304.8 mm (12.0 in)	1.245 mm (.049 in)
306.072 mm (12.05 in)	37.34 mm (12.1 in)	1.27 mm (.05 in)

In Table 2 we show examples of how the diagonal might be expressed and reported.



Table 2. Examples of Usage			
True Diagonal	Preferred	Acceptable	Not Acceptable
13.7931 in	13.8 in	13.79 in	14 in
12.0942 in	12.1 in	12.09 in	12 in
12.1253 in	12.1 in	12.13 in	12 in

ASPECT RATIO: This is handled in the next section (13.1.2). Briefly, the aspect ratio α is the ratio of the horizontal size to the vertical size:

$$\alpha = H/V,$$

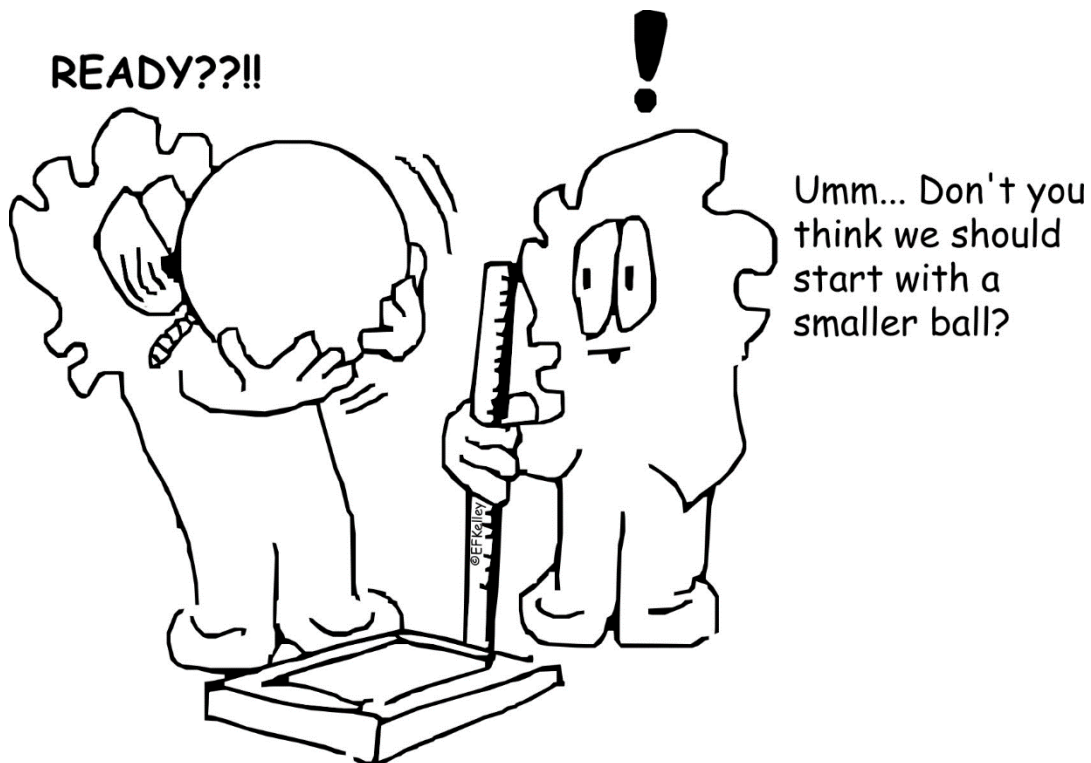
and may be useful in calculations. Note, however, sometimes the aspect ratio is not a precisely known quantity but is often rounded to a convenient ratio of integers, e.g., 4×3 , 16×9 , etc.

Table 3. Summary of useful relationships between size variables.																	
Some equations are only true for square pixels. See Table 4 for definitions.																	
Expression	Square px Only?	N_H	N_V	N_T	H	V	A	P_H	P_V	P	S_H	S_V	S	a	D	α	Comments
$A = HV$					*	*	*										Exact
$H = N_H P_H$		*			*			*									Very small error
$H = \frac{D}{\sqrt{\left(\frac{N_V}{N_H}\right)^2 + 1}}$	Sq. px Only	*	*		*										*		
$H = \frac{\alpha D}{\sqrt{\alpha^2 + 1}}$	Sq. px Only				*										*	*	Aspect ratio may not be known accurately due to rounding.
$V = N_V P_V$			*			*			*								Very small error
$V = \frac{D}{\sqrt{\left(\frac{N_H}{N_V}\right)^2 + 1}}$	Sq. px Only	*	*			*									*		
$V = \frac{D}{\sqrt{\alpha^2 + 1}}$	Sq. px Only					*									*	*	Aspect ratio may not be known accurately due to rounding.
$a = P_H P_V$								*	*					*			
$a = P^2$	Sq. px Only									*				*			
$a = A/N_T$				*			*							*			Exact
$D = \sqrt{H^2 + V^2}$					*	*									*		Exact
$D = \sqrt{(P_H N_H)^2 + (P_V N_V)^2}$		*	*					*	*						*		
$D = \sqrt{P_2(N_H^2 + N_V^2)}$	Sq. px Only	*	*							*					*		
$D = \sqrt{\left(\frac{N_H}{S_H}\right)^2 + \left(\frac{N_V}{S_V}\right)^2}$		*	*								*	*			*		
$D = \sqrt{N_H^2 + N_V^2}/S$	Sq. px Only	*	*										*		*		
$P = \frac{D}{\sqrt{N_H^2 + N_V^2}}$	Sq. px Only	*	*							*					*		
$\alpha = H/V$					*	*										*	
$\alpha = N_H/N_V$	Sq. px Only	*	*													*	



Table 4. Variables Related to Size.

P_H, P_V, P	Pixel pitch for horizontal, vertical, and for square pixels for which $P_H = P_V = P$
N_H, N_V	Number of pixels in the horizontal and vertical direction
S_H, S_V, S	Pixel spatial frequency for horizontal, vertical, and for square pixels ($S = 1/P$)
D	Diagonal measure of the screen, expressed in units of distance
H, V	Horizontal and vertical measure of the screen
α	Aspect ratio $\alpha = H/V$
A	Area of viewable display surface ($A = HV$)
a	Rectangular area allocated to each pixel ($a = P_H P_V$)

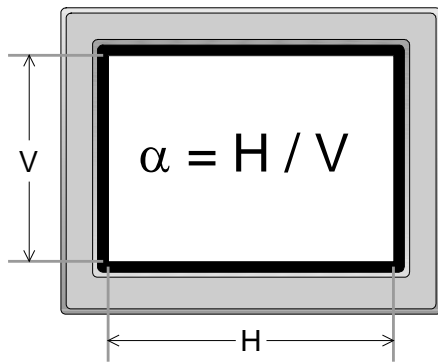




13.1.2 ASPECT RATIO & DISPLAY FORMATS

This section describes the various methods to calculate and report the aspect ratio of a display. Generally speaking, the aspect ratio is not often considered to be a precise measure of the display, but rather an approximation of the actual width-to-height ratio in order to indicate the shape of the display surface in a simple manner. If the display surface is not square, there are two orientations in which the display can be placed. If the largest side is placed horizontally, we refer to this as the **landscape** orientation. If the largest side is placed vertically, we refer to this as the **portrait** orientation. Here are the variables used in this subsection:

P_H, P_V, P	Pixel pitch for horizontal, vertical, and for square pixels for which $P_H = P_V = P$
N_H, N_V	Number of pixels in the horizontal and vertical direction
D	Diagonal measure of the screen
H, V	Horizontal and vertical measure of the screen
α	Aspect ratio



The aspect ratio is defined as width-to-height ratio of the active viewing area of a screen:

$$\alpha = H/V.$$

Note that this refers to the active area of the screen, the part of the observable screen viewed and addressed to display information. Although the aspect ratio could be expressed as a decimal number, it is usually expressed as a ratio such as H:V, e.g., 4:3, 16:9, etc, with the horizontal aspect given first in the ratio. In fact, the aspect ratio is often expressed as a ratio of small integers. For example, a landscape display may have a horizontal size of 300 mm and vertical size of 200 mm, then the aspect ratio is

Landscape: $\alpha = H/V = 300/200 = 1.5 = 3/2$, or expressed as a ratio, 3:2. If that same display were used in the portrait orientation the aspect ratio would still be

the width-to-height ratio

Portrait:

expressed as a ratio, 2:3.

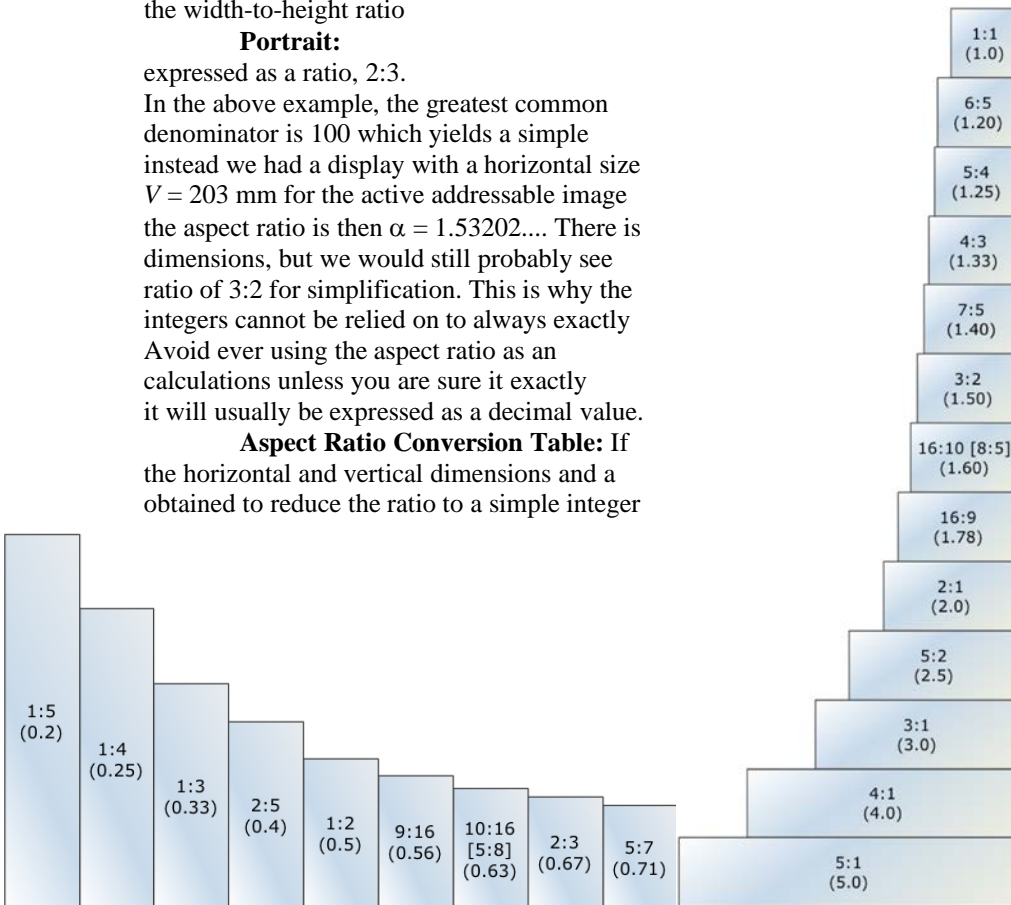
In the above example, the greatest common denominator is 100 which yields a simple instead we had a display with a horizontal size $V = 203$ mm for the active addressable image the aspect ratio is then $\alpha = 1.53202....$ There is dimensions, but we would still probably see ratio of 3:2 for simplification. This is why the integers cannot be relied on to always exactly Avoid ever using the aspect ratio as an calculations unless you are sure it exactly it will usually be expressed as a decimal value.

Aspect Ratio Conversion Table: If the horizontal and vertical dimensions and a obtained to reduce the ratio to a simple integer

$$\alpha = H/V = 200/300 = 0.6667 = 2/3, \text{ or}$$

divisor in for both the numerator and integer ratio. However, suppose that of $H = 311$ mm and a vertical size of producing area. The decimal value for no common divisor for these the display listed as having an aspect aspect ratio when expressed as a ratio of specify the actual width-to-height ratio. accurate number in formulas and expresses the ratio of H/V , in which case

one is calculating the aspect ratio from greatest common divisor cannot be ratio, the following table is provided to help determine the closest aspect ratio expressed in integer number ratios where the integers are not greater than 20. Determine the decimal aspect ratio; then find the closest decimal aspect ratio in the table; finally, use the ratio of integers for the simplified aspect ratio. Be reasonable using the table: You may find that quoting a 12:11 aspect ratio (1.0909) is so close to 11:10 (1.1) that you would rather use 11:10; or 17:13 (1.3077) is sufficiently close to 4:3 (1.3333) that you would more reasonably use 4:3. Most of



the time people used simple ratios where the integers were usually less than 10. Use of the 16:9 standard format for HDTV



has complicated the matter, hence all the fractional aspect ratios using integers less than 20 are presented for your interest and inspection. The table assumes the landscape orientation. If the portrait orientation is used, simply invert the decimal ratio ($1/\alpha$), find the appropriate integer ratio in the table, then reverse the ratio for use with the portrait orientation.

Table 1. Aspect-Ratio Conversion

Decimal aspect ratios less than 5:1 converted to integer ratios using integer numbers no greater than 20.
Ratios in parentheses are some equivalent aspect ratios sometimes used in industry.

Decimal Aspect Ratio	Integer Aspect Ratio	Decimal Aspect Ratio	Integer Aspect Ratio	Decimal Aspect Ratio	Integer Aspect Ratio	Decimal Aspect Ratio	Integer Aspect Ratio
1	1 : 1	1.2727...	14 : 11	1.7143...	12 : 7	2.6	13 : 5
1.0526...	20 : 19	1.2857...	9 : 7	1.7273...	19 : 11	2.6667...	8 : 3
1.0556...	19 : 18	1.3	13 : 10	1.75	7 : 4	2.7143...	19 : 7
1.0588...	18 : 17	1.3077...	17 : 13	1.7778...	16 : 9	2.75	11 : 4
1.0625...	17 : 16	1.3333...	4 : 3 (8:6)	1.8	9 : 5 (18:10)	2.8	14 : 5
1.0667...	16 : 15	1.3571...	19 : 14	1.8182...	20 : 11	2.8333...	17 : 6
1.0714...	15 : 14	1.3636...	15 : 11	1.8333...	11 : 6	2.8571...	20 : 7
1.0769...	14 : 13	1.375	11 : 8	1.8571...	13 : 7	3	3 : 1
1.0833...	13 : 12	1.3846...	18 : 13	1.875	15 : 8	3.1667...	19 : 6
1.0909...	12 : 11	1.4	7 : 5 (14:10)	1.8889...	17 : 9 (34:18)	3.2	16 : 5
1.1	11 : 10	1.4167...	17 : 12	1.9	19 : 10 (9.5:5)	3.25	13 : 4
1.1111...	10 : 9	1.4286...	10 : 7	2	2 : 1 (20:10)	3.3333...	10 : 3
1.1176...	19 : 17	1.4444...	13 : 9 (26:18)	2.1111...	19 : 9	3.4	17 : 5
1.1333...	17 : 15	1.4545...	16 : 11	2.125...	17 : 8	3.5	7 : 2
1.1429...	8 : 7	1.4615...	19 : 13	2.1429...	15 : 7	3.6	18 : 5
1.1538...	15 : 13	1.5	3 : 2 (6:4)	2.1667...	13 : 6	3.6667...	11 : 3
1.1667...	7 : 6	1.5385...	20 : 13	2.2	11 : 5	3.75	15 : 4
1.1765...	20 : 17	1.5455...	17 : 11	2.2222...	20 : 9	3.8	19 : 5
1.1818...	13 : 11	1.5556...	14 : 9 (28:18)	2.25	9 : 4	4	4 : 1
1.1875...	19 : 16	1.5714...	11 : 7	2.2857...	16 : 7	4.25	17 : 4
1.2	6 : 5 (12:10)	1.5833...	19 : 12	2.3333...	7 : 3	4.3333...	13 : 3
1.2143...	17 : 14	1.6	8 : 5 (16:10)	2.375	19 : 8	4.5	9 : 2
1.2222...	11 : 9 (22:18)	1.625	13 : 8	2.4286...	17 : 7	4.6667...	14 : 3
1.2308...	16 : 13	1.6364...	18 : 11	2.4	12 : 5	4.75	19 : 4
1.25	5 : 4 (10:8)	1.6667...	5 : 3	2.5	5 : 2	5	5 : 1
1.2667...	19 : 15	1.7	17 : 10 (8.5:5)	2.5714...	18 : 7		

Depending upon the quantities one has available to perform the aspect ratio calculation, here are a variety of formulas to calculate the decimal aspect ratio: $\alpha = H/V = N_H/N_V$. See Table 3 of the last section (13.1.1) for a complete tabulation of useful relationships between variables.

Table 2. Decimal Aspect Ratio Formulas

Non-square pixels	Either Square or Non-Square	Square pixels
$\alpha = \frac{H}{V} = \frac{N_H P_H}{N_V P_V}$	$\alpha = \frac{H}{V}$	$\alpha = \frac{H}{V} = \frac{N_H}{N_V}$
	$V = \frac{D}{\sqrt{\alpha^2 + 1}}$	
	$H = \frac{\alpha D}{\sqrt{\alpha^2 + 1}}$	



Table 3. Some Pixel-Array Formats Encountered in the Industry

Class	Code	Name	α	α (numeric)	N_H	N_V	N_T	(*)	Applications
<10 kpx			1:1	1.000	60 X	60	3,600	*	
			3:2	1.500	96 X	64	6,144	*	
			~3:2	1.477	96 X	65	6,240	*	
			1:1	1.000	80 X	80	6,400	*	
			~4:3	1.350	108 X	80	8,640		
10 kpx			1:1	1.000	120 X	120	14,400	*	
			~1:1	1.067	128 X	120	15,360		
			~1:1	1.100	132 X	120	15,840	*	
			1:1	1.000	128 X	128	16,384		
			1:1	1.000	128 X	128	16,384	*	
			1:1	1.000	132 X	132	17,424	*	
		quarter, quarter VGA	4:3	1.333	160 X	120	19,200	*	
			5:4	1.250	160 X	128	20,480	*	
			2:1	2.000	208 X	104	21,632		
			4:3	1.333	176 X	132	23,232	*	
			1:1	1.000	160 X	160	25,600	*	
	qCIF	quarter CIF	11:9	1.222	176 X	144	25,344	*	
			1:1	1.000	160 X	160	25,600		
			~4:3	1.309	216 X	165	35,640		
			~6:5	1.182	208 X	176	36,608	*	
			13:11	1.182	208 X	176	36,608	*	
			3:2	1.500	240 X	160	38,400		
			5:4	1.250	220 X	176	38,720		
			4:3	1.333	240 X	180	43,200	*	
			1:1	1.000	240 X	240	57,600		
			16:9	1.778	320 X	180	57,600	*	
			~3:2	1.481	308 X	208	64,064		
		quarter K	1:1	1.000	256 X	256	65,536	*	
			20:13	1.538	320 X	208	66,560		
	qVGA	quarter VGA	4:3	1.333	320 X	240	76,800	*	
			3:1	3.000	480 X	160	76,800	*	
			~3:2	1.467	352 X	240	84,480		
			8:5	1.600	384 X	240	92,160	*	
			5:3	1.667	400 X	240	96,000	*	
100 kpx	CIF	common image format	11:9	1.222	352 X	288	101,376	*	
			1:1	1.000	320 X	320	102,400	*	
			~11:10	1.063	340 X	320	108,800	*	
			16:5	3.200	640 X	200	128,000	*	
			~16:9	1.765	480 X	272	130,560		
			~7:5	1.363	432 X	317	136,944	*	
	hVGA	half VGA	(16:6) 8:3	2.667	640 X	240	153,600		
	HVGA		3:2	1.500	480 X	320	153,600	*	Portable/Hand-held devices
			16:10 (8:5)	1.600	512 X	320	163,840	*	
			4:3	1.333	480 X	360	172,800	*	



Class	Code	Name	α	α (numeric)	N_H	N_V	N_T	(*)	Applications
200 kpx			2:1	2.000	640 X	320	204,800	*	
200 kpx			1:1	1.000	480 X	480	230,400		
	nHD		16:9	1.778	640 X	360	230,400		
		half K	1:1	1.000	512 X	512	262,144	*	
			~3:2	1.509	640 X	424	271,360		
			25:11	2.273	800 X	352	281,600		
300 kpx	VGA	video graphics array	4:3	1.333	640 X	480	307,200	*	
		(MPEG2 mode)	3:2	1.500	720 X	480	345,600		MPEG2
			1:1	1.000	600 X	600	360,000		
			16:9	1.778	800 X	450	360,000		
			16:10 (8:5)	1.600	768 X	480	368,640	*	
			5:3	1.667	800 X	480	384,000		
			3:2	1.500	768 X	512	393,216		
400 kpx			~17:10	1.767	848 X	480	407,040	*	
			~16:9	1.775	852 X	480	408,960	*	
			~16:9	1.777	853 X	480	409,440	*	
	WVGA		18:10 (9:5)	1.800	864 X	480	414,720		
			2:1	2.000	960 X	480	460,800		
	SVGA	super VGA	4:3	1.333	800 X	600	480,000	*	
	UWVGA		32:15	2.133	1024 X	480	491,520		
500 kpx			1:1	1.000	720 X	720	518,400		
	qHD	quarter HD	16:9	1.778	960 X	540	518,400		
			16:9	1.778	1024 X	576	589,824	*	
			16:10 (8:5)	1.600	1024 X	640	655,360	*	
			3:2	1.500	960 X	640	614,400		Portable/Hand-held devices
	XGA	extended GA	4:3	1.333	1024 X	768	786,432	*	
	WXGA		3:2	1.500	1152 X	768	884,736		
	HDTV	HDTV (HDTV2)	16:9	1.778	1280 X	720	921,600	*	
	WXGA+	Wide XGA+	5:3	1.667	1280 X	768	983,040	*	
			4:3	1.333	1152 X	864	995,328	*	
1 Mpx		Sun Micro-systems	1.28:1	1.280	1152 X	900	1,036,800		
			~16:9	1.771	1360 X	768	1,044,480	*	
		one K	1:1	1.000	1024 X	1024	1,048,576	*	Air traffic control
			~16:9	1.779	1366 X	768	1,049,088		
			~1:1	1.055	1080 X	1024	1,105,920	*	
			16:10 (8:5)	1.600	1280 X	800	1,024,000		
			16:9	1.778	1440 X	810	1,166,400		
	QVGA	Quad VGA	4:3	1.333	1280 X	960	1,228,800	*	
	WXGA+	wide XGA+	16:10 (8:5)	1.600	1440 X	900	1,296,000		
	SXGA	super extended GA	5:4	1.250	1280 X	1024	1,310,720	*	



Class	Code	Name	α	α (numeric)	N_H	N_V	N_T	(*)	Applications
			16:9	1.778	1600	X 900	1,440,000		
1 Mpx	SXGA+	stretched SXGA	4:3	1.333	1400	X 1050	1,470,000	*	
	WSXGA		25:16	1.563	1600	X 1024	1,638,400	*	
			5:4	1.250	1440	X 1152	1,658,880		
			16:10 (8:5)	1.600	1638	X 1024	1,677,312	*	
	WSXGA+	wide SXGA +	16:10 (8:5)	1.600	1680	X 1050	1,764,000	*	
	UXGA	ultra XGA	4:3	1.333	1600	X 1200	1,920,000	*	
2 Mpx	HDTV / FHD	high-definition TV, Full HD	16:9	1.778	1920	X 1080	2,073,600	*	HDTV
			~19:10	1.896	2048	X 1080	2,211,840	*	
	WUXGA	widescreen UXGA	16:10 (8:5)	1.600	1920	X 1200	2,304,000	*	
	WDXGA		16:9	1.778	2048	X 1152	2,359,296		
			~4:3	1.294	1760	X 1360	2,393,600	*	
			4:3	1.333	1920	X 1440	2,764,800		
			21:9 (7:3)	2.370	2560	X 1080	2,764,800		Cinemascope, CinemaWide
3 Mpx	QXGA	quadruple extended GA	4:3	1.333	2048	X 1536	3,145,728	*	
			5:4	1.250	2000	X 1600	3,200,000	*	
			16:9	1.778	2560	X 1440	3,686,400		
			3:2	1.500	2400	X 1600	3,840,000		Digital Camera
4 Mpx	WQXGA	wide XXGA	16:10 (8:5)	1.600	2560	X 1600	4,096,000	*	
		two K	1:1	1.000	2048	X 2048	4,194,304	*	
			16:9	1.776	2784	X 1568	4,365,312		Digital Camera
			4:3	1.333	2560	X 1920	4,915,200		Digital Camera
5 Mpx			4:3	1.333	2592	X 1944	5,038,848		Digital Camera
			16:9	1.782	3008	X 1688	5,077,504		Digital Camera
	QWXGA+	quad wide XGA+	16:10 (8:5)	1.600	2880	X 1800	5,184,000		
	QSXGA	quadruple SXGA	5:4	1.250	2560	X 2048	5,242,880	*	
			~4.5:1	4.548	4912	X 1080	5,304,960		3D Panorama
6 Mpx			3:2	1.500	3072	X 2048	6,291,456		
	WQSXGA	wide quadruple SXGA	15.6:10	1.563	3200	X 2048	6,553,600		
7 Mpx			16:9	1.776	3552	X 2000	7,104,000		Digital Cinema
	QUXGA	quadruple UXGA	4:3	1.333	3200	X 2400	7,680,000	*	
			~6.6:1	6.622	7152	X 1080	7,724,160		3D Panorama
			4:3	1.333	3264	X 2448	7,990,272		Digital Cinema
8 Mpx	Q-HDTV	quadruple HDTV, quad HD, 4k TV	16:9	1.778	3840	X 2160	8,294,400	*	HDTV
			3:2	1.500	3600	X 2400	8,640,000		Digital Cinema



13.1 PHYSICAL, MECHANICAL — Section 13.1



13.1

Class	Code	Name	α	α (numeric)	N_H	N_V	N_T	(*)	Applications
		4k x 2k	~2:1	1.896	4096	X 2160	8,847,360		Digital Cinema
9 Mpx	WQUXGA	wide QUXGA	16:10 (8:5)	1.600	3840	X 2400	9,216,000	*	
10 Mpx			16:9	1.767	4240	X 2400	10,176,000		Digital Camera
			16:9	1.776	4320	X 2432	10,506,240		Digital Cinema
			~2:1	1.873	4496	X 2400	10,790,400		Digital Cinema
			~2.5:1	2.563	5536	X 2160	11,957,760		Panorama
10 Mpx		4k x 3k	4:3	1.333	4000	X 3000	12,000,000		Digital Cinema
			~4:3	1.291	4096	X 3172	12,992,512	*	
			~4.4:1	4.414	8192	X 1856	15,204,352		Panorama
			3:2	1.500	4800	X 3200	15,360,000		Digital Camera
		4k x 4k	1:1	1.000	4096	X 4096	16,777,216	*	
20 Mpx			3:2	1.500	5520	X 3680	20,313,600		Digital Camera
			16:9	1.777	6000	X 3376	20,256,000		Digital Camera
			~6.7:1	6.690	12416	X 1856	23,044,096		Panorama
			3:2	1.500	6000	X 4000	24,000,000		Digital Camera
			~3:2	1.506	6144	X 4080	25,067,520		Digital Camera
	WHSXGA		~8:5	1.563	6400	X 4096	26,214,400		
30 Mpx			~5:4	1.251	6144	X 4912	30,179,328		Digital Camera
	HUXGA		4:3	1.333	6400	X 4800	30,720,000		
	Q-QHDTV, UHDTV	ultra HDTV, quad quad HDTV, 8k TV	16:9	1.778	7680	X 4320	33,177,600		HDTV
			~3:2	1.498	7360	X 4912	36,152,320		Digital Camera
	WHUXGA		16:10 (8:5)	1.600	7680	X 4800	36,864,000		Digital Cinema
*Supported with bit-mapped files in collections									



13.1.3 IMAGE-SIZE REGULATION

DESCRIPTION: We assess the regulation of image size with content by measuring the change of image height and width as a function of the average luminance of the display. This measurement has some history in CRT displays where it is important to access the stability of the high voltage supply as a function of displayed image. Since more current is required at higher luminance, the accelerating voltage may decrease, and thus the size of the raster will increase as the brightness of the image increases, if the power supply has less than perfect regulation. **Units:** in percentage of image size. **Symbol:** none.

APPLICATION: Displays that exhibit raster scanning such as CRTs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Display a single-pixel wide line along all outer edges—the periphery—of the pixel array, and arrange the spatially resolved luminance meter to measure the position of the centroid of each line-luminance profile at the ends of the major and minor axes of the screen (see the figure), that is, at the locations of the center of the edges of the periphery box. The positioning uncertainty of the linear positioners need only be less than a half-width of a pixel for most purposes over the entire screen area. The normal viewing direction should be maintained.

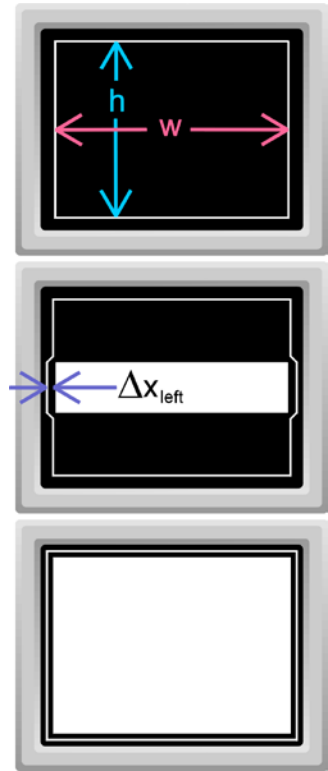
For optical measurement, use large-area box pattern (the interior box) surrounded by visible edges or lines as shown in figure. The solid box should extend to within five pixels of the surrounding white line. The black space separating the white interior box and the surrounding white periphery line should be as narrow as possible for maximum loading yet the periphery line should be distinctly resolvable. (Smaller-sized white targets with more black space between top and bottom surrounding white lines may reveal poor high-frequency regulation on raster-scanned CRT displays with vertical scan at the refresh frequency, typically 60 Hz to 180 Hz.)

PROCEDURE: Use an array detector and translation stage to locate the centroids of the line profiles at their intersections of the major and minor axes of the display surface. Measure the horizontal separation or width w between line positions the right and left centroids of the single-pixel-line periphery as a function of luminance of the gray level displayed in the interior box as the gray level is stepped at 0 % (black), 25 %, 50 %, 75 % and 100 % or white (for an 8-bit display these levels would correspond to 0, 63, 127, 191, and 255 out of 255 gray levels). Similarly, measure the vertical separation or height h between the line positions of the top and bottom edges of the single-pixel-line periphery (not shown in the figure). If any image size is well regulated, the changes in the positions of the border lines as a function of image content would be negligible.

ANALYSIS: Image size regulation is the difference between the greatest and the least distance measured between the lines, expressed as a percentage of the total image size minimums, $100\% \times (\max - \min) / \min$.

REPORTING: Report the maximum change in raster size as a percentage of the total screen linear dimension to no more than three significant figures.

COMMENTS: Accuracy of the x, y translation stage should be better than 0.1% of display screen linear dimension for raster distortion measurements.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis and Reporting		
Image size vs. interior box luminance.		
Gray Level of interior box	Width (mm) w	Height (mm) h
100%	384.175	286.842
75%	384.099	286.791
50%	383.870	286.715
25%	383.837	286.650
0% (black)	383.819	286.588
min	383.819	286.588
max	384.175	286.842
max-min	0.356	0.254
Image Size Regulation	0.093%	0.089%



13.2 STRENGTH

It is important to note that these procedures stress the structure or surface of the display and could irreparably damage the display surface or its electronic substructure

13.2.1 TORSIONAL STRENGTH

ALIAS: static twist loading, mechanical deflection, mechanical strength, flexing test, bending test, deformity test

DESCRIPTION: We measure the mechanical strength of a display panel, module, or enclosed system (DUT) to assure that no damage will occur for fixed amount of flexing for a force placed on a corner for testing, when 3 corners are secured, and force is applied to the fourth for strength testing.

Torsional strength of the display or monitor refers to its abilities to withstand uneven forces or loads, such as when it is secured in one or more places and flexed in another. This is a proof test (not a characterization) of the strength of the DUT to see if it survives in terms of the deflection or load when a prescribed load is applied. Although proof of the DUT's survival may be in terms of magnitude of displacement, this is not a force or displacement test, or a test of rigidity or flexibility. In other words, we don't deliberately stress the display to its breaking or damage point in order to find the limits of the strength, and we don't attempt to measure the deflection distance as a function of applied force. This is considered a pass-fail test.

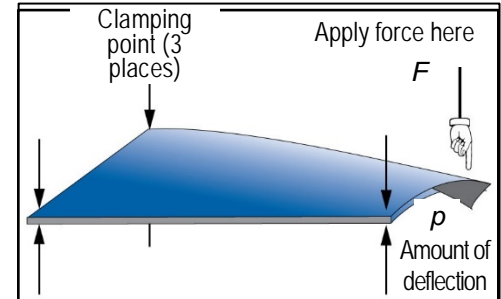
Method: Clamp the DUT in three corners using a method which will not damage the display. Clamping distance must be within 2% of each edge of the DUT. With three corners of the DUT held fixed a force F is applied to the free corner until it reaches the full specified force F_L . Under such a force, the free corner of the DUT will experience a displacement p that should be not more than the specified maximum displacement p_L . The display meets the required torsional strength if it can withstand the full force for a specified time t and show a displacement of no more than p .

Note: At the discretion of the interested parties this could be used as a limit test to test either the maximum strength (maximum resistance to force) or deflection to the breaking point.

APPLICATION: The DUT may be bare display panels, modules, or enclosed systems which are to be tested for torsional strength when 3 corners are secured and the 4th is deflected. This measurement could also apply to subcomponents of a display, such as glass or intermediate structures.

This test is intended for the non-operational mode but could be done in the operational mode for some cases at the discretion of the interested parties, such as the display integrator and manufacturer. However, even for the non-operational mode, operation of the display is critical to determine if it passes or fails, since some damage might only be determined from the operation of the display.

SETUP: No standard setup conditions are required. However, temperature and humidity requirements as well as soak time might be used at the discretion of the interested parties. [1] The display assembly should be rigidly braced at any three corners and subjected to a force applied at the fourth. The contact area of the clamping fixture should be no more than 5 % of the horizontal (H) and vertical (V) size of the active area. That is, all contact regions should be ≤ 5 % of any linear dimension of the active area of the screen. The clamp design should be agreed upon by the interested parties prior to any testing. The test may be performed with the display either in an operating or non-operating mode as needed.



The figure shows an exaggerated amount of bending for a rigid display. It is for effect only.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Report of test results

Parameter	Magnitude		Units	
Load, F_L	10		kg-force	
Operational / Non-Operational	Non-Op.			
Number of cycles, n	10		-- none --	
Duration of application, t_L	20		s	
Deflection maximum, p_L	7		mm	
Corner	Upper Left	Upper Right	Lower Left	Lower Right
Maximum deflection p_{max}	7	7	7	7
Strength verified all corners:	Yes	Yes	Yes	Yes
Damage:	No	No	No	No



Load Parameters:

- Operating load:** (Optional) For an operating display under test, the force $F_L = F_1$ is to be determined as per agreement between display integrator and manufacturer; this specification is an option.
- Non-operating load:** For a non-operating display, the force $F_L = F_2$ is to be determined as per agreement between display integrator and manufacturer.
- Direction of load:** Perpendicular to the plane of the DUT in both directions.
- Test cycles:** The force test will be applied n times in each direction for each corner of the display ($m = 2 \times 4 \times n$ cycles total for operational and non-operational tests—two sides, four corners, n applications of force).
- Dynamics:** Constant force for a $t_L = 5$ s minimum duration.
- Clamping Force:** (Optional) If the DUT is mounted in a bezel then it may be necessary to specify a clamping force F_c when attempting to measure the deflection p of the forced corner, since some of the deflection will arise from the compression of the bezel. If the DUT does not have a protective bezel and you can attach the brace to a solid circuit board (or equivalent), then this force need not be specified.
- Units:** The force may be expressed in N (newtons, generally not often used), kilogram-force (the force of gravity on a mass of one kilogram, ugh! SI is writhing in pain!), or whichever unit is mutually agreed upon by all interested parties.

Panel Reaction to the Applied Force: Full-rated load is attained, and the corner of the display is flexed not more than the specified maximum deflection distance p_L while the full rated load is applied. Prepare to measure the applied force F and the resulting deflection of the screen p . Optionally, full-rated deflection may be the item to be measured rather than a fixed load.

- Withstand:** Each tested corner of the display is able to withstand the full-load force F_L for n times in each direction for a duration of t_L each time.
- Deflection:** Under the application of the full-load force each tested corner must deflect in the direction of the force by no more than the maximum deflection distance p_L .

PROCEDURE: Clamp the DUT rigidly at three corners. Note the original position of the corner z_0 without a force applied. Gradually apply a force to the free corner until the full-load force F_L is attained. Hold that force for a duration time of t_L , measure the new position of the corner z , and calculate the deflection $p = z - z_0$ from the corner's position before the force is applied. Then gradually release the force. Repeat application and removal of the force n times. Repeat the procedure for the opposite direction of application of the force. Repeat this procedure for each corner of the DUT.

ANALYSIS: Calculation of deflection during the course of the measurement: $p = z - z_0$. Determine the maximum deflection p_{max} for each corner for both directions and all applications of the force.

REPORTING: Report all measurement conditions and results.

COMMENTS: The parameters of this measurement are to be determined by all interested parties (such as the display integrator and manufacturer). **CAUTION:** This measurement can be a destructive test. It may permanently alter or destroy the display. Breakage of the

display can potentially result in exposing materials that may be hazardous to health.



Variable List for Torsional Strength	
Parameters Values Mutually Agreed to by All Interested Parties	
F	Force applied perpendicularly to the display's corner
F_L	Full-load force to be applied to one corner at a time
$F_L = F_1$	Force on corner while display is operating (optional)
$F_L = F_2$	Force on corner while display is not operating
t_L	Minimum duration of full-load application F_L
n	Number of times force is applied in each direction
m	Total number of applications of F_L , $m = 2 \times 4 \times n$
p_L	Maximum deflection specified for application of F_L
p_{max}	Maximum measured deflection for each corner
p	Deflection for application of F_L
z_0	Starting position of corner before force is applied
z	Final position of corner during the application of F_L

[1] If structurally relevant materials which are part of the (DUT) are known to be sensitive to humidity or temperatures in the normal test range, then standardized test and soak conditions should be used. This might apply to polymer-based substrates or components.



13.2

13.2.2 FRONT-OF-SCREEN STRENGTH

ALIAS: Point load test

DESCRIPTION: Measure the strength of the screen by applying a specific force at the center of the screen by a loading object used to a simulated finger to determine if the display suffers any damage. This is considered a pass-fail test.

Note: At the discretion of the interested parties this could be used to test either the maximum strength (maximum resistance to force) or deflection to the breaking point.

APPLICATION: The DUT may be bare display panels, modules, or enclosed systems which are to be tested for torsional strength when 4 corners are secured to allow for deflection at the center of the screen for an applied force. This measurement could also apply to subcomponents of a display, such as glass or intermediate structures.

An alternate method could be for enclosed, finished display products, where the load is applied perpendicular (normal) to the display in the center by use of a force gauge instrument or equivalent.

The test may be done for the non-operational mode or operational mode. However, if performed for the non-operational mode, operation of the display before and after the test is critical to determine if it passes or fails, since some damage might only be determined from the operation of the display.

SETUP: No standard setup conditions are needed. Temperature and humidity requirements and soak time may be used at the discretion of the interested parties.

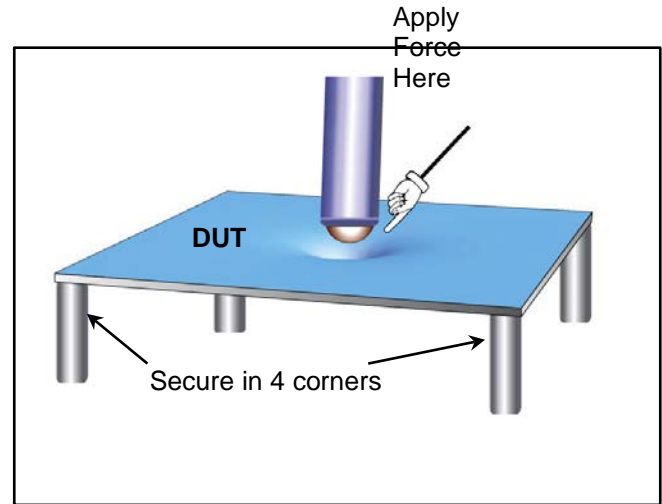
Unless otherwise specified, the DUT should be rigidly braced at the four corners with each support covering not more than 5 % of the horizontal H and vertical V dimensions of the DUT. The displayed pattern should be static and have a video content the produces the greatest sensitivity to the applied force at the center of the screen. The force should be applied at the center of the screen within ± 3 % of the screen diagonal.

Load Parameters:

- Loading object contact surface area:** $a = 10$ mm ± 1 mm diameter
- Loading object contact material:** Elastomer of Shore 60A ± 10 durometer
- Applied force:** The full-load force F_L applied to the center of the screen with the simulated finger. Applied gradually to reach F_L within no shorter than 0.5 s and no longer than 10 s, held for t_L , then released within no shorter than 0.5 s and no longer than 10 s.
- Angle of application:** Normal to the face of the display
- Probe tip geometry:** Hemispherical
- Applied pressure duration:** The time interval t_L over which the DUT is subjected to full load force F_L .
- Dynamics:** Single application of constant force F_L for duration t_L .
- Units:** The force may be expressed in N (newtons, generally not often used), kilogram-force (the force of gravity on a mass of one kilogram, ough! SI is writhing in pain!), or whichever unit is mutually agreed upon by all interested parties.

Display Reaction to the Applied Force: The type of damage or degradation that is unacceptable is to be determined between display integrator and manufacturer—all interested parties. Examples of types of damage would be physical breakage, discoloration of any image, or any permanent remnants of the force having been applied.

- Acceptable Performance:** Specification of performance after the force has been removed and after the recovery time period has passed. Damage or degradation tolerance of any displayed image due to front of panel displacement under pressure must be specified under agreement by interested parties.
- Recovery Time:** Recovery time t_R after the force is removed for the display to return to an acceptable performance.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Report of test results

Parameter	Magnitude	Units
Full-load force, F_L	3	kg-force
Operational / Non-Operational	Non-Op.	-- none --
Duration of application, t_L	5	s
Recovery time specified, t_R	10	sec
Center strength criterion met?	yes	



PROCEDURE: Apply the force F_L to the center of the screen for a period t_L and then remove it (see above specifications in Setup). Wait for the recovery time t_R to elapse and inspect the screen for acceptability.

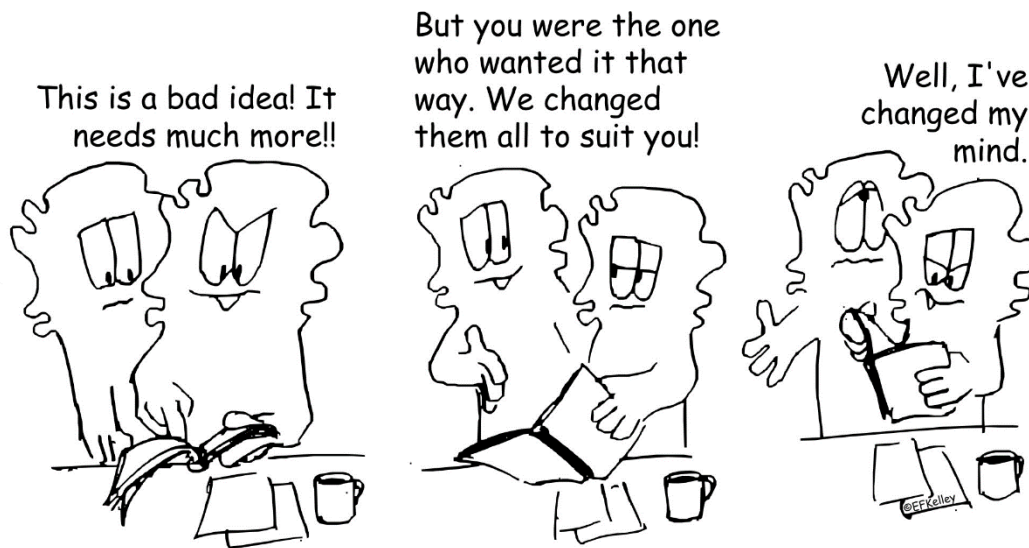
ANALYSIS: None, other than observation of the screen after the force is removed.

REPORTING: Report all measurement conditions and results.

COMMENTS: CAUTION: This measurement can be a destructive test. It may permanently alter or destroy the display. Breakage of the display can potentially result in exposing materials that may be hazardous to health.



Variable List for Front-of-Screen Strength	
Parameters Values Mutually Agreed to by All Interested Parties	
F_L	Full-load force to be applied to one corner at a time
t_L	Minimum duration of full-load application F_L
t_R	Maximum recovery time after application of F_L





13.2.3 WOBBLE

ALIAS: monitor stability, mechanical stability, display head instability, display head rocking

DESCRIPTION: Monitors and other displays configurations which are on height-adjustable stands may become less stable when the display head is raised upward to its upper height range. As the display head is adjusted higher, it may wobble, such that the head tilts left to right and in the reverse direction. It may rock and oscillate until mechanical forces stabilize it.

Wobble from instability can be in two directions, front-to-back, and left-to-right / right-to-left. For this measurement we address the left/right wobble as indicated by the arrows in the figure to the right.

APPLICATION: Displays on height-adjustable stands or other mounts which may induce instability and allow the display head to wobble. This is often most severe for larger and wide-format displays on height-adjustable stands when they adjusted for maximum height.

SETUP: No standard setup conditions apply.

Equipment needed: (1) Video recording camera, (2) level or plumb device, and (3) ruler

2kg force with a suitable probe. An alternate force can be used if it the 2kg force not adequate for the display under test.

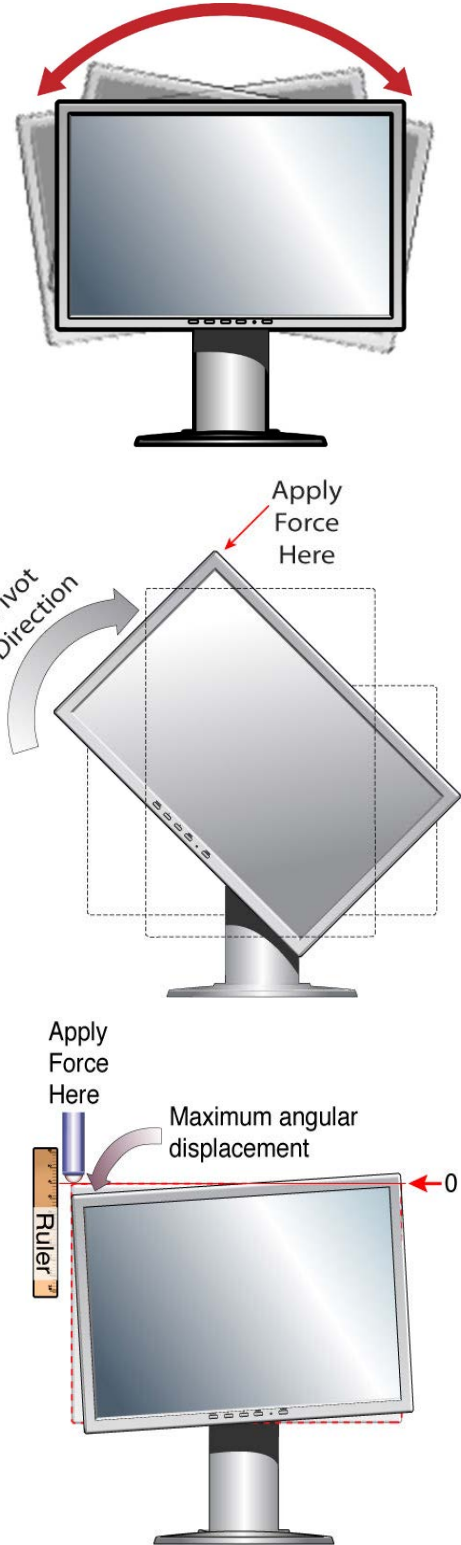
OTHER SETUP CONDITIONS: Raise the display head to the maximum height level which the stand allows. This is the point for maximum mechanical instability for which the display should be evaluated. Assure the monitor is perpendicular to the surface, and level at the top.

Optional: Secure the base to the surface. Determine the correct edge for the force to be applied. If the display has a pivot function, then the force is applied on the upper side of the display which is opposite from the pivot direction. For example, a pivot function in the clockwise (CW) direction is shown. The left side of the display tilts upward to achieve the pivot. For this case, the force to test for stability per this measurement would be applied to assure wobble is measured in the CCW direction, or downward on the top left side of the display head. Other examples within this section are based on the example where the display has a pivot function in the CW direction.

1. **Level:** Assure that the top of the display head is level.
2. **Ruler:** Secure a ruler next to the display head top surface when it is level and determine a reference point numerically on the scale. The ruler will remain stable when the display head is pushed down and released and will be in the video recording to give a reference for amount of displacement.
3. **Video Camera:** Set the video camera securely in position to record the vertical displacement of the display head with a clear view of the ruler.
4. **Force applied to distend display head:** Place the force on the corner of the display head which will be distended. Note the amount of displacement, since this will be the maximum distance, for $t=0$.
5. **Record the movement:** With the display head statically distended due to the applied force, begin the recording of the vertical movement of the corner of the display head with respect to the ruler. Rapidly release the load, so that the the display head will go into its wobbling condition. Continue recording until the display head has fully stabilized.
6. **Analyze the recorded output:** Using a video editing software tool of choice, analyze the recorded video to determine how magnitude of displacement and number of up/down cycles take place for the display wobble.

PROCEDURE: Determine stability (or wobble) based upon two parameters with respect to time: magnitude of displacement (distance) from the stable state and number of cycles until the display head has stabilized.

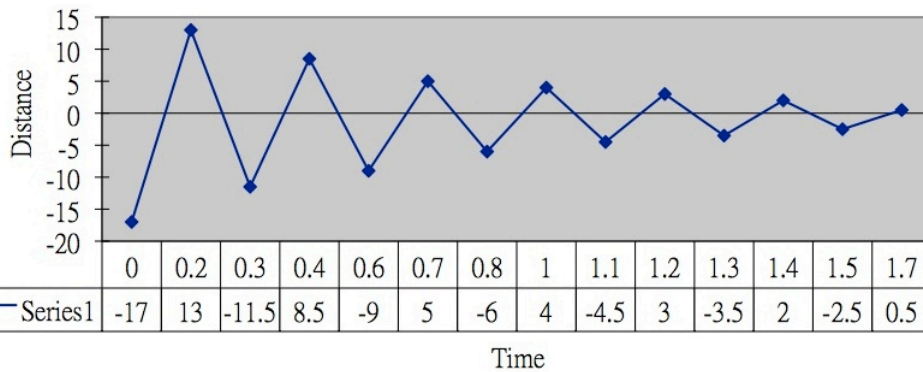
1. Apply a force of 2kg to the top of the display within 2% of the edge which will be forced in the downward position. The probe should be something which simulates a finger, such as Elastomer of Shore 60A \pm 10 durometer
2. This should be the force which will displace the display head without toppling the display. It is option of the tester to





secure the base of the stand to a surface, in which case the force applied will be the force which causes the maximum angular displacement of the display head.

- Measure the displacement from parallel of the corner of the top of the display. That displacement will be the distance from 0 for $T=0$. Since the corner of the display is pushed downward, the distance will be negative. Report the negative displacement as point 1 in the reporting table, along with time (0 for the 1st static point).
- Assure that a suitable ruler is secured along the
- With a suitable video recorder recording the process, release the 2kg force.
- Record the display movement until it stabilizes, and no more movement exists.
- Evaluate the video to determine displacement distance, direction of displacement, and time. Look for maximum displacement points and determine the direction and the time, until the display head wobble motion subsides.
- Make a table to record the displacement points, the direction of displacement, the distance, and the time like the example shown.
- Plot the data.
- Plot the positive peaks and then the negative peaks until they reach zero. This gives the envelope of the wobble time, or the decay curve.



SAMPLE DATA

Reporting example

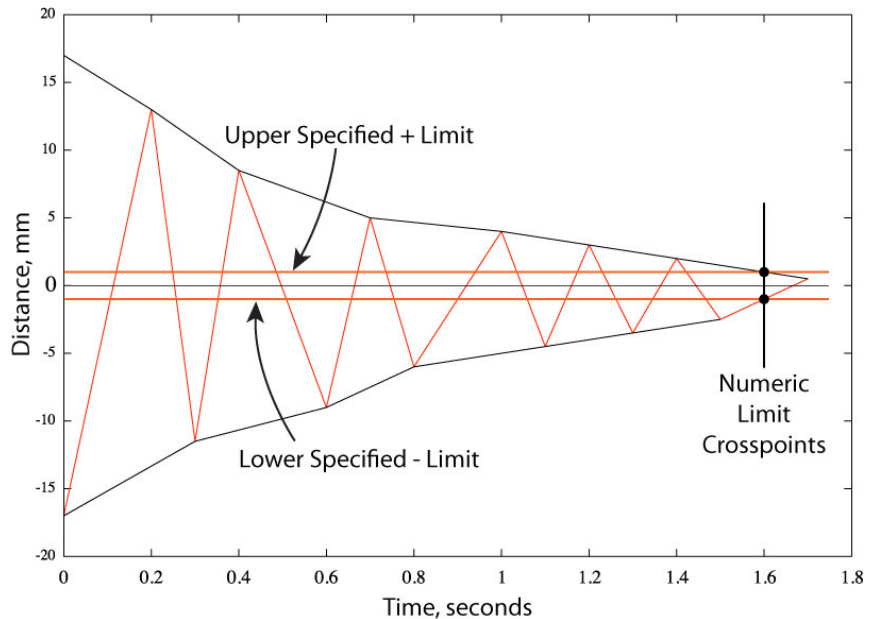
Point	Time (s)	Distance (Displacement) (mm)
1	0	-17
2	0.2	13
3	0.3	-11.5
4	0.4	8.5
5	0.6	-9
6	0.7	5
7	0.8	-6
8	1	4
9	1.1	-4.5
10	1.2	3
11	1.3	-3.5
12	1.4	2
13	1.5	-2.5
14	1.7	0.5

REPORTING: Report the following characteristics.

- Full height from the surface top to the the top of the display head when it is level and adjusted to full height
- Time to reach stability (Damping time from $T=0$ until stabilization has been reached)
- Number of cycles to reach stability
- Maximum displacement distance (Static case with the 2kg force applied)
- Time to reach a specified limit, if one is given.

Interested parties may produce a specification for this test based any of the following parameters

- Load force
- Maximum static displacement
- Number of cycles of wobble
- Time until the display has stabilize
- What constitutes stabilization



COMMENTS: (1) Perpendicularity: We assume that the display head is level, or perpendicular to a plumb line, for the stable (non-wobbling) state. An imaginary line drawn across the top of the display head would therefore be zero. If the display is not level, then its offset from level must be added or subtracted from the distances obtained for the wobble measurements.



13.3 GEOMETRY

Geometrical distortions of the presented image can arise from several mechanisms: Whenever a lens exists between the observer and the display that generates the image, geometric distortions can be created such as with HMDs, near-eye displays (NEDs), front-projection displays, rear-projection displays, and HUDs. Scanning displays such as flying spot or CRTs may also exhibit geometrical distortions. Currently we provide for the following measurements:

13.3.1 CONVERGENCE

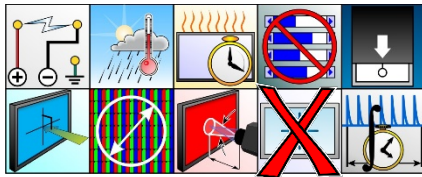
DESCRIPTION: We measure the separation or convergence errors between primaries of the color display. Convergence is measured at nine (or 25) specified points on the screen and reported as the maximum distance between any two primary colors. **Units:** mm or px. **Symbol:** none.

Lack of adequate convergence (misconvergence) effects the true appearance of colored features in an image and can contribute to the loss of resolution of the display. Misconvergence can arise from inadequate alignment of multibeam scanning devices (e.g., CRTs, flying-spot displays) or projection systems. Projection systems may also experience a misconvergence from achromaticity of the projection lens as well as any misalignment of color primary source image planes.

Units: **Symbol:**

APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

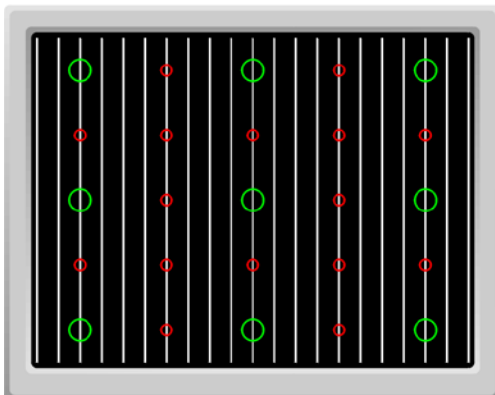
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



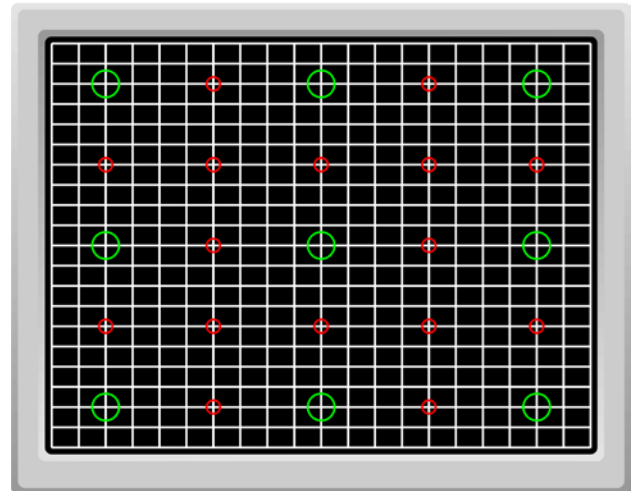
OTHER SETUP CONDITIONS: Display a full-screen crosshatch test pattern and arrange the spatial luminance meter to measure the line luminance profiles at nine (or 25) positions—see the figure. The corner points are 1/10 the screen height and 1/10 the screen width from the edge of the image displaying surface. Positioning uncertainty need only be ± 0.1 px, the normal direction should be maintained.

For visual examination, inspect convergence using crosshatch pattern consisting of at least 20 vertical and 20 horizontal lines each 1-pixel wide, spaced no more than 5 % of the screen width/height apart. For optical measurement at standard test locations shown in the figures, use V-grille and H-grille video patterns consisting of vertical and horizontal lines each from 1 to 5-pixels wide. Use of lines greater than 1 or 2 pixels increases luminance profile sampling and can improve measurement repeatability on shadow mask CRTs.

Vertical Measurement Grille

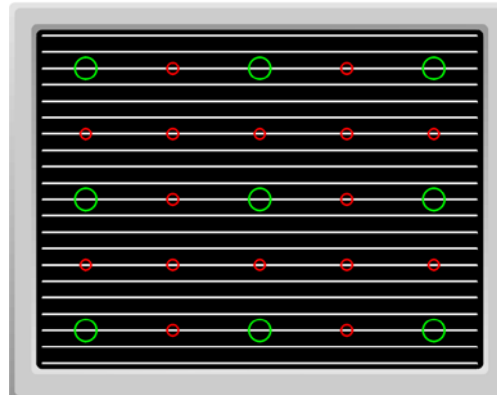


20x20 Single-Pixel-Wide Grid



● 9-point locations
○ 25-point locations

Horizontal Measurement Grille



PROCEDURE: Visually examine the crosshatch pattern for overall convergence performance. Record measurements at any screen location where significant misconvergence is apparent, but not characterizable at the standard nine or twenty-five



screen test locations. Separately measure vertical and horizontal misconvergence at nine standard screen test points (optionally 25 screen test points) using appropriate horizontal and vertical grille test patterns of lines from 1 px to 5 px wide for each primary, e.g., R, G, B. Use a spatially-calibrated array detector to measure the luminance profiles of the lines at each measurement location and determine the horizontal x_R, x_G, x_B , and vertical position y_R, y_G, y_B of the centroid of each horizontal and vertical luminance profile in units of mm or px, $(x_R, y_R)_i, (x_G, y_G)_i, (x_B, y_B)_i$, for $i=1, 2, \dots 9$ (or 25) at each measurement location. It is sometimes helpful to average a number of luminance profiles to provide a more reproducible measurement of the centroids of the line profiles.

ANALYSIS: From the collected centroid data, determine the line separations $(\Delta x_{BR}, \Delta y_{BR})_i$ between the blue and red line centroids at each of the measurement locations $i=1, 2, \dots 9$ (or 25) [optionally determine the green with-respect-to red line centroid separation $(\Delta x_{GR}, \Delta y_{GR})_i$], where

$$(\Delta x_{BR} = x_B - x_R)_i, (\Delta y_{BR} = y_B - y_R)_i, \quad (1)$$

and, optionally

$$(\Delta x_{GR} = x_G - x_R)_i, (\Delta y_{GR} = y_G - y_R)_i. \quad (2)$$

Determine the maximum horizontal and vertical separations for blue with-respect-to red lines, and optionally green with-respect-to red lines.

REPORTING: Report the number of samples used along with their average value. Report $(\Delta x_{BR}, \Delta y_{BR})_i$ for all measurement locations $i=1, 2, \dots 9$ (or 25) to no more than three significant figures. Report the maximum line separations as the convergence error in mm of pixels. If a number of luminance profiles are averaged to provide the centroid measurement, the number of profiles that are averaged should be reported.

COMMENTS: For color CRTs, measurements of centroids can be subject to large errors depending on the detector sampling and the aliasing between the beam and the shadowmask. Repeat measurements of luminance profiles at slightly different screen positions, offset by sub-pixel distances, if possible, in order to randomize the sampling pattern of the luminance profile. Be sure your number of measurement samples is adequate. Acceptable results have been obtained using at least seven samples. Each sample is offset from the specified pixel position by $\pm 1, \pm 2$, and ± 3 pixel spacings for a total of seven measurements including the starting location. It is important to report whether the convergence measurements are made sequentially or simultaneously, e.g., for white. In CRTs, space-charge repulsion forces between electron beams can significantly impact the convergence of the beams at the screen.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Analysis and Reporting (Sample Data)		
Number of samples averaged per measurement location =		7
	Horizontal Separation	Vertical Separation
9 point	$\Delta x_{BR} = x_B - x_R$ (mm)	$\Delta y_{BR} = y_B - y_R$ (mm)
1	-0.343	0.142
2	0.038	0.089
3	-0.086	0.287
4	-0.089	0.201
5	-0.061	0.109
6	-0.13	0.213
7	-0.371	0.229
8	-0.003	0.201
9	-0.231	0.170
maximum:	-0.371	0.287



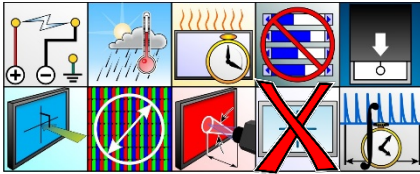
13.3.2 LINEARITY

DESCRIPTION: We measure the relation between the actual measured position of a pixel compared to the intended position to quantify effects of nonlinearity.

Nonlinearity can be thought of as an unintentional variation in pixel density. Nonlinearity of scanned displays (such as projection, flying spot, or CRT displays) degrades the preservation of scale in images across the display. **Units:** in percentage of image size. **Symbol:** none.

APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Display vertical or horizontal lines spaced no more than 5% of the addressable screen and arrange the spatial luminance meter to measure the position of the centroid of each line luminance profile—see the figure. Positioning uncertainty need only be ± 0.1 px; the normal direction should be maintained.

For optical measurements of the positions of the lines shown in the figure, use V-grille and H-grille video patterns consisting of vertical and horizontal lines each 1-pixel wide, equally spaced (in pixel units) by no more than 5% of the addressable screen.

PROCEDURE: Use an array detector to locate center of line profiles in conjunction with an (x, y)-translation stage to measure screen x,y coordinates of points where video pattern vertical lines intersect horizontal centerline of screen and where horizontal lines intersect vertical centerline of the display screen. Tabulate (x, y) positions (in mm or px) of equally spaced lines (nominally 5% addressable screen apart) along major (horizontal or longest centerline) and minor (vertical or shortest centerline) axes of the screen.

ANALYSIS: Nonlinearity is the difference between the spacings measured between each pair of adjacent lines minus the average of all the measured spacings, expressed as a percentage of average spacing.

If both scans are truly linear, the differences in the positions of adjacent lines would be constant. The departures of these differences is the nonlinearity. The linearity of the horizontal scan is determined from measured x-positions, x_i for $i = 0, 1, 2, \dots, 10$, of equally indexed vertical lines on the screen, such lines being equally spaced by pixel count. The linearity of the vertical scan is similarly determined using the y-positions, y_i for $i = 0, 1, 2, \dots, 10$, of horizontal lines. The spacing between adjacent lines is computed as the difference in x-positions, $\Delta x = x_{i+1} - x_i$ for $i = 0, 1, 2, \dots, 9$ of vertical lines. The line spacings are used to determine the horizontal non-linearity characteristic. Similarly, differences in y-positions $\Delta y = y_{i+1} - y_i$ for $i = 0, 1, 2, \dots, 9$ of horizontal lines are calculated to determine vertical non-linearity characteristic. For each adjacent pair of lines, a nonlinearity value is computed and plotted:

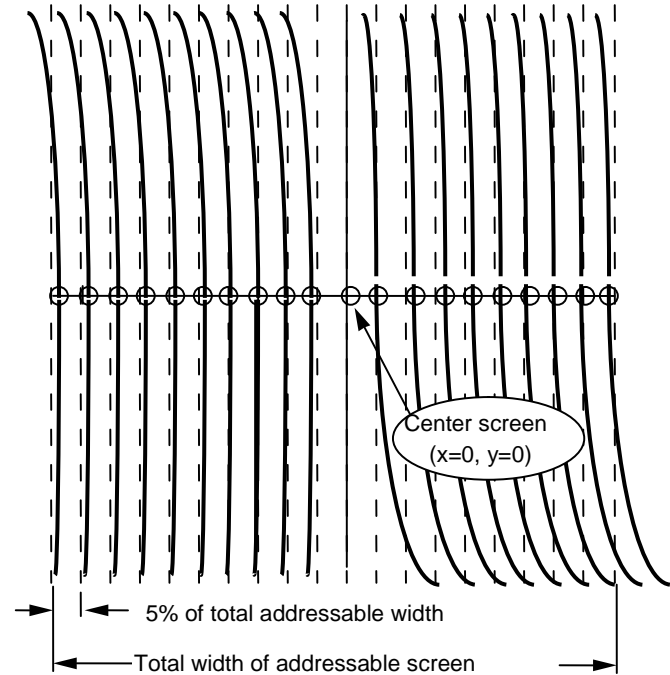
$$\text{Horizontal nonlinearity} = 100\% \times (\Delta x_i - \Delta x_{\text{avg}}) / \Delta x_{\text{avg}}, \text{ for } i = 0, 1, 2, \dots, 10.$$

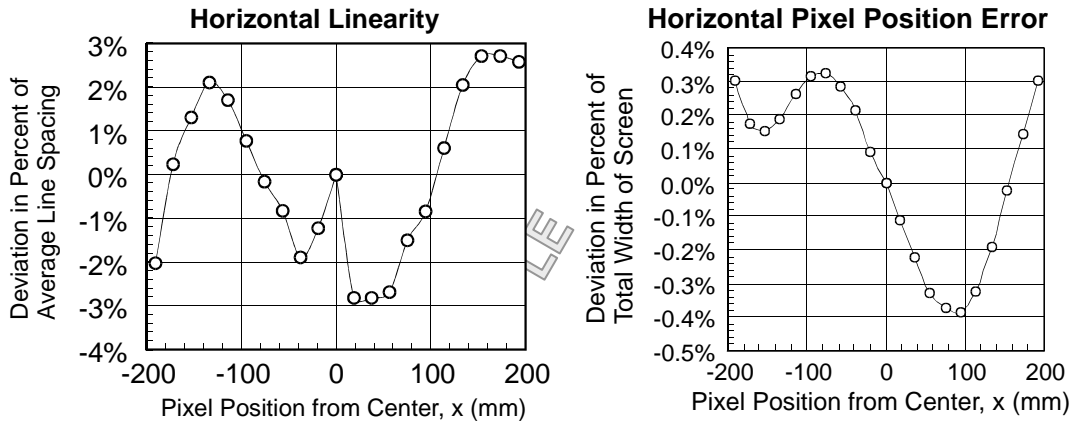
$$\text{Vertical nonlinearity} = 100\% \times (\Delta y_i - \Delta y_{\text{avg}}) / \Delta y_{\text{avg}}, \text{ for } i = 0, 1, 2, \dots, 10.$$

Optionally, *pixel position error* can be computed and plotted from the measured positions of the lines if one chooses the average line spacing to be the reference. Then a linear reference grid, $(x_{\text{iref}}, y_{\text{iref}})$ for $i = 0, 1, 2, \dots, 10$, can be numerically constructed. The measured positions of lines are then compared to the reference grid. Differences between actual measured positions of lines and the corresponding reference position of that line is expressed as a percentage of the total screen size in that direction to provide pixel position errors:

$$\text{Horizontal pixel position error} = 100\% \times (x_i - x_{\text{iref}}) / H \text{ for } i = 0, 1, 2, \dots, 10.$$

$$\text{Vertical pixel position error} = 100\% \times (y_i - y_{\text{iref}}) / V \text{ for } i = 0, 1, 2, \dots, 10.$$





REPORTING: Report the four maximum nonlinearity values for the (1) top half, (2) bottom half, (3) left side, and (4) right side of the screen to no more than three significant figures. Optionally, report the four maximum pixel position errors for the (1) top half, (2) bottom half, (3) left side, and (4) right side of the screen to no more than three significant figures.

COMMENTS: Accuracy of (x, y)-translation stage should be better than 0.1% of display screen linear dimension for raster distortion (linearity, waviness) measurements.

—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Analysis and Reporting				
	x-Position of Vertical Lines (mm)		y-Position of Horizontal Lines (mm)	
<i>i</i>	Left Side	Right Side	Top	Bottom
10	-190.8	193.1	143.0	-143.1
9	-172.1	173.3	128.3	-129.0
8	-153.0	153.5	114.1	-114.7
7	-133.7	133.7	99.9	-100.4
6	-114.2	113.9	85.6	-86.1
5	-94.8	94.5	71.3	-71.7
4	-75.5	75.4	57.1	-57.4
3	-56.5	56.3	42.8	-43.0
2	-37.6	37.5	28.5	-28.6
1	-18.8	18.8	14.3	-14.3
0	0.0	0.0	0.0	0.0
Maximum Linearity Errors				
	2.10%	2.81%	2.35%	0.98%
Maximum Pixel Position Errors				
	0.33%	0.38%	0.15%	0.11%



13.3 PHYSICAL, MECHANICAL — Section 13.3



13.3

Vertical waviness of horizontal lines:

$$V = \text{average}(y_{Ti} - y_{Bi})$$

Top: $H_T: e = [\max(y_i - y_{Ti}) - \min(y_i - y_{Ti})] / V$

Center $H_C: e = [\max(y_i - y_{Ci}) - \min(y_i - y_{Ci})] / V$

Bottom $H_B: e = [\max(y_i - y_{Bi}) - \min(y_i - y_{Bi})] / V$

Horizontal waviness of vertical lines:

$$H = \text{average}(x_{Ri} - x_{Li})$$

Left $V_L: e = [\max(x_i - x_{Li}) - \min(x_i - x_{Li})] / H$

Center $V_C: e = [\max(x_i - x_{Ci}) - \min(x_i - x_{Ci})] / H$

Right $V_R: e = [\max(x_i - x_{Ri}) - \min(x_i - x_{Ri})] / H$

In the example below we show only sample data for horizontal waviness of vertical lines.

REPORTING: Report peak-to-peak waviness error as a percentage of linear screen dimension to no more than three significant figures. Report large area distortions to no more than three significant figures.

COMMENTS: Accuracy of (x, y)-translation stage should be better than 0.1% of display screen linear dimension. The above rigorous method can be used for displays even where the corners are not well defined (such as being out of focus or where there is a corner vignette).

—SAMPLE DATA ONLY—											
Do not use any values shown to represent expected results of your measurements.											
Analysis and Reporting											
Horizontal Waviness of Vertical Lines: 0.08%											
$H = \text{average}(x_{Ri} - x_{Li}) = \mathbf{381.91}$ mm											
LEFT SIDE				CENTER				RIGHT SIDE			
PTP error, e	0.29	mm		PTP error, e	0.11	mm		PTP error, e	0.2	mm	
Waviness	0.08%			Waviness	0.03%			Waviness	0.05%		
Offset (s_L)	-190.31			Offset (s_{CV})	0.0096			Offset (s_R)	191.60		
Slope (m_L)	0.0024			Slope (m_{CV})	0.0019			Slope (m_R)	0.0014		
x	y	x_{Li}	error	x	y	x_{Ci}	error	x	y	x_{Ri}	error
-190.12	145.67	-189.95	-0.17	0.28	145.52	0.29	-0.01	191.92	146.25	191.80	0.12
-190.07	137.16	-189.97	-0.09	0.33	137.16	0.28	0.05	191.80	137.16	191.79	0.00
-190.07	121.92	-190.01	-0.06	0.30	121.92	0.25	0.06	191.72	121.92	191.77	-0.05
-190.07	106.68	-190.05	-0.02	0.25	106.68	0.22	0.04	191.72	106.68	191.75	-0.03
-190.07	91.44	-190.09	0.02	0.20	91.44	0.19	0.02	191.69	91.44	191.73	-0.03
-190.07	76.20	-190.12	0.05	0.13	76.20	0.16	-0.03	191.69	76.20	191.71	-0.01
-190.07	60.96	-190.16	0.09	0.08	60.96	0.13	-0.05	191.69	60.96	191.68	0.01
-190.09	45.72	-190.20	0.10	0.05	45.72	0.10	-0.05	191.67	45.72	191.66	0.01
-190.17	30.48	-190.23	0.06	0.03	30.48	0.07	-0.04	191.62	30.48	191.64	-0.02
-190.22	15.24	-190.27	0.05	0.03	15.24	0.04	-0.01	191.62	15.24	191.62	0.00
-190.25	0.00	-190.31	0.06	0.00	0.00	0.01	-0.01	191.62	0.00	191.60	0.02
-190.32	-15.24	-190.35	0.02	-0.03	-15.24	-0.02	-0.01	191.59	-15.24	191.58	0.02
-190.40	-30.48	-190.38	-0.02	-0.08	-30.48	-0.05	-0.03	191.57	-30.48	191.55	0.01
-190.42	-45.72	-190.42	0.00	-0.10	-45.72	-0.08	-0.02	191.52	-45.72	191.53	-0.02
-190.42	-60.96	-190.46	0.03	-0.10	-60.96	-0.11	0.01	191.44	-60.96	191.51	-0.07
-190.42	-76.20	-190.49	0.07	-0.13	-76.20	-0.14	0.01	191.41	-76.20	191.49	-0.07
-190.47	-91.44	-190.53	0.06	-0.15	-91.44	-0.17	0.02	191.44	-91.44	191.47	-0.03
-190.55	-106.68	-190.57	0.02	-0.18	-106.68	-0.20	0.02	191.49	-106.68	191.45	0.05
-190.65	-121.92	-190.61	-0.05	-0.20	-121.92	-0.23	0.02	191.52	-121.92	191.42	0.09
-190.75	-137.16	-190.64	-0.11	-0.23	-137.16	-0.26	0.03	191.47	-137.16	191.40	0.06
-190.80	-146.15	-190.67	-0.14	-0.28	-146.15	-0.27	-0.01	191.34	-146.69	191.39	-0.05



13.3.4 LARGE-AREA DISTORTIONS

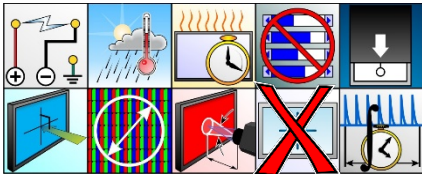
DESCRIPTION: We detail calculations that use measured pixel positions from a displayed target to characterize common distortions known as trapezium (trapezoid or keystone), rotation, orthogonality, and pincushion. **NOTE: The data collected are exactly that obtained in the previous measurement**

14.3.3 Waviness. Units: in percentage of image size for dimensional distortions and degrees for rotational distortions.

Symbols: δ_{TH} , δ_{TV} , θ_{RH} , θ_{RV} , δ_O , δ_{PT} , δ_{PB} , δ_{PL} , δ_{PR} .

APPLICATION: Any display that can have its image distorted such as by a lens or raster scan.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Exactly as in the previous measurement 14.3.3 Waviness.

PROCEDURE: Same as in previous 14.3.3 Waviness.

ANALYSIS: There are two types of large-area distortions that are characterized: linear distortions known as trapezium, rotation, and orthogonality; and a quadratic distortion known as pincushion (or barrel).

LINEAR DISTORTIONS: Use the linear regression results of the previous measurement 14.3.3 Waviness to establish the locations of the cardinal points p depicted in the figure where p can be A, B, D, E, C, F, G, J, and K associated with the intersections of the linear-fit lines at locations (x_p, y_p) , where

$$x_p = \frac{m_h m_v + s_h}{1 - m_h m_v}, \quad y_p = \frac{m_v s_h + m_v}{1 - m_h m_v}$$

and where for each p the horizontal lines (h) and vertical lines (v) have subscripts:

Subscript Notation: T = top, C = center, B = bottom, L = left, R = right									
$p =$	A	B	D	E	C	F	G	J	K
$h =$	T	T	T	CH	CH	CH	B	B	B
$v =$	L	CV	R	L	CV	R	L	CV	R

Trapezium, rotation, and orthogonality measurements are based upon the linear fits to the data as follows:

Trapezium: Horizontal trapezium (or trapezoid) δ_{TH} characterizes any linear picture height change in the horizontal direction. Vertical trapezium (or trapezoid) δ_{TV} characterizes any linear picture width change in the vertical direction:

$$\delta_{TH} = 2 \frac{(\overline{AG} - \overline{DK})}{(\overline{AG} + \overline{DK})} \times 100\%,$$

where

$$\overline{AG} = \sqrt{(x_A - x_G)^2 + (y_A - y_G)^2}$$

and

$$\overline{DK} = \sqrt{(x_D - x_K)^2 + (y_D - y_K)^2}.$$

$$\delta_{TV} = 2 \frac{(\overline{AD} - \overline{GK})}{(\overline{AD} + \overline{GK})} \times 100\%,$$

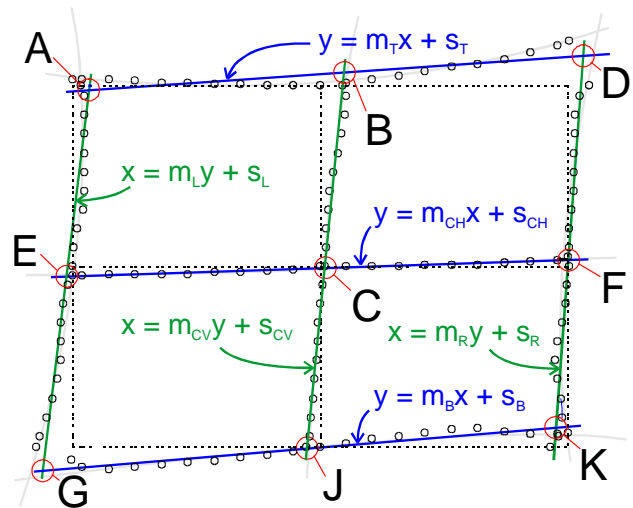
where

$$\overline{AD} = \sqrt{(x_A - x_D)^2 + (y_A - y_D)^2}$$

and

$$\overline{GK} = \sqrt{(x_G - x_K)^2 + (y_G - y_K)^2}.$$

Rotation: Each major and minor axis can have a different rotation from the horizontal and vertical. The rotation of horizontal axis (major axis for a landscape display) is θ_{RH} and the rotation of the vertical axis (minor axis for a landscape display) is θ_{RV} :



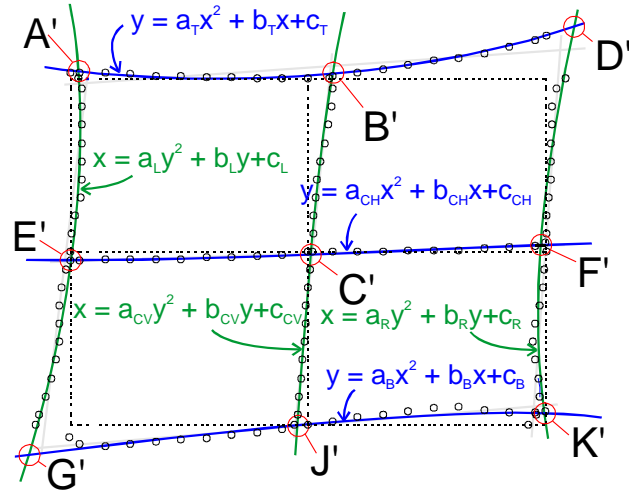


$$\theta_{RH} = \arctan\left(\frac{y_F - y_E}{x_F - x_E}\right) \text{ and } \theta_{RV} = \arctan\left(\frac{y_B - y_J}{x_B - x_J}\right).$$

Orthogonality: A measure of how much the screen looks like a parallelogram (an alternative name for this distortion is parallelogram) is the orthogonality given by:

$$\delta_O = 2 \frac{(\overline{AK} - \overline{DG})}{(\overline{AK} + \overline{DG})} \times 100\%, \text{ where } \overline{AK} = \sqrt{(x_A - x_K)^2 + (y_A - y_K)^2} \text{ and } \overline{DG} = \sqrt{(x_D - x_G)^2 + (y_D - y_G)^2}.$$

PINCUSHION (QUADRATIC) DISTORTIONS: Fit a 2nd-order polynomial curve to each of the six lines, three vertical and three horizontal. Determine the new locations of the cardinal points A', B', D', E', C', F', G', J', and K' associated with the intersections of the quadratic-fit lines. The closed-form solutions to the intersection locations (x_p, y_p) are the roots of fourth-order polynomials and are uglier than a mud fence. Usually, numerical methods are used rather than attempting to fill the page with the analytical solution. (Probably the crudest way to solve for the intersections is to use a spreadsheet: Select an x_H value along a horizontal line near an intersection. Determine the corresponding y value for the horizontal line $y = a_H x_H^2 + b_H x_H + c_H$ and put this y back into the equation for the vertical intersecting line $x_V = a_V y^2 + b_V y + c_V$. Find the x_H that gives the same x_V , then $x_p = x_H = x_V$ and $y_p = y$. Kids, don't try this at home.)



$$\delta_{PT} = 2 \frac{(y_A + y_D) - y_B}{(\overline{A'G'} + \overline{D'K'})} \times 100\%,$$

$$\delta_{PB} = 2 \frac{(y_G + y_K) - y_J}{(\overline{A'G'} + \overline{D'K'})} \times 100\%,$$

$$\delta_{PL} = 2 \frac{(x_A + x_G) - x_E}{(\overline{A'D'} + \overline{G'K'})} \times 100\%,$$

$$\delta_{Pr} = 2 \frac{(x_D + x_K) - x_F}{(\overline{A'D'} + \overline{G'K'})} \times 100\%,$$

where

$$\overline{A'G'} = \sqrt{(x_{A'} - x_{G'})^2 + (y_{A'} - y_{G'})^2},$$

$$\overline{D'K'} = \sqrt{(x_{D'} - x_{K'})^2 + (y_{D'} - y_{K'})^2},$$

$$\overline{A'D'} = \sqrt{(x_{A'} - x_{D'})^2 + (y_{A'} - y_{D'})^2},$$

and

$$\overline{G'K'} = \sqrt{(x_{G'} - x_{K'})^2 + (y_{G'} - y_{K'})^2}.$$

REPORTING: Report large area distortions to no more than three significant figures.

COMMENTS: Accuracy of (x, y)-translation stage should be better than 0.1% of display screen linear dimension for raster distortion (linearity, waviness) measurements. If an accurate grid can be obtained (either a transparent mask that covers a direct-view display or a grid on a projection screen), it may be possible to obtain the location of the cardinal points from a direct measurement using the grid without the use of a positioning system. This is particularly true for well-behaved displays where these distortions are small. In such a case, the location of the cardinal points is determined using a pattern where single-pixel white lines mark the center lines (or nearly center) and the edges or even single white pixels can be placed at the cardinal points.



—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Large Area Distortions					
Pincushion Distortion from Polynomial Fit, mm					
Ax	Ay	Ex	Ey	Bx	By
-190.1	145.7	0.3	145.6	191.8	146.2
Hx	Hy	CTRx	CTRy	Fx	Fy
-190.2	-0.2	0.0	0.0	191.6	0.1
Dx	Dy	Gx	Gy	Cx	Cy
-190.8	-146.2	-0.2	-145.9	191.4	-145.6
AD + BC	583.66				
AB + CD	764.09		Top pin	0.125%	
AD - BC	0.15		Bot pin	0.012%	
AB - CD	-0.29		Right pin	0.011%	
AC	479.94		Left pin	0.050%	
BD	481.57				
Trapezium, Rotation and Orthogonality from Linear Fit, mm					
Ax	Ay	Ex	Ey	Bx	By
-190.0	145.4	0.3	145.7	191.8	146.0
Hx	Hy	CTRx	CTRy	Fx	Fy
-190.3	-0.2	0.0	0.0	191.6	0.1
Dx	Dy	Gx	Gy	Cx	Cy
-190.7	-146.2	-0.3	-145.9	191.4	-145.5
AD + BC	583.20	H-trapezium		0.049%	
AB + CD	763.81	V-trapezium		-0.078%	
AD - BC	0.14	Rotation Major-Axis		4.05	degrees
AB - CD	-0.30	Rotation Minor-Axis		-11.1	degrees
AC	479.68	Orthogonality		-0.341%	



14. ELECTRICAL MEASUREMENTS

There are two areas of concern regarding electrical measurements: (1) power consumption and power-supply characteristics, and (2) the associated light efficiencies. Accordingly, we divide this section into two main parts.

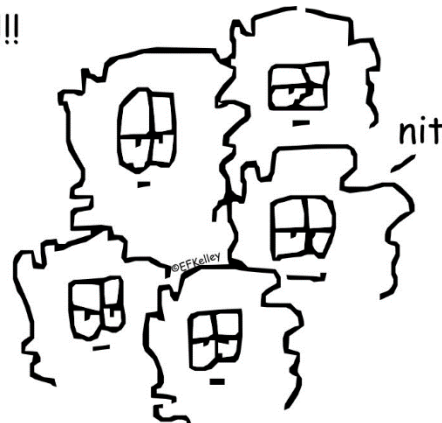
Electrical Power Measurements: Making an electrical power measurement on a display assumes that the circuitry is accessible or the display is powered by a power source separate from the display. In many cases the DUT can have an integrated power source that does not lend itself to measurement such as in a laptop computer. In such cases many would be hesitant to break into the enclosure and tap into the powering lines to the display. In such cases the manufacturing data may be the only source of information as to the power consumption of the DUT. *Note: If any measurement in 14.2 EFFICIENCIES will be made, be sure to measure the power with a white full screen in addition to any other pattern otherwise chosen.*



Efficiency: The term “luminous efficiency” in the CIE definition means the number of lumens per optical power (watts, W) of radiation. The term “luminous efficacy” is used by the CIE to characterize the luminous flux per watt of electrical energy input (lm/W). “Efficiency” is more familiar to many. Generally speaking, the efficiency characterizes how well the display converts electrical power into visible light. Note that § 14.2.1 Frontal Luminance Efficiency uses the term “luminance” not “luminous.” Since some displays can emit quite a bit of light away from the normal without much desirable information content, we felt that the frontal luminance efficiency was a reasonable metric to introduce. It is, perhaps, a better metric for characterizing display performance than the luminous efficacy (“efficiency”). Luminous efficacy (“efficiency”), on the other hand, is a type of power ratio that characterizes the visible “power” output in all directions vs. the electrical power input (the luminous flux is what some have called a “light watt”). One obvious advantage using the frontal luminance efficiency is that neither a large integrating sphere, goniophotometric sampling, nor other expensive apparatus is needed to make the measurement provided a power measurement or characterization is available.

Recently, 2010, a new “efficiency” metric has been introduced that is very similar to the frontal luminance efficiency. Some call it “energy efficiency” and adopted as an evaluation criterion in certain countries. The most technically descriptive name would be “frontal intensity efficiency” and is included in this main efficiency section (§ 14.2.3).

Frontal luminance efficiency!!!
Who would be stupid enough
to introduce a new metric?!



International Committee
for Display Metrology

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



14.1 SUPPLY AND POWER-CONSUMPTION METRICS

Concern for the measurement of electrical power required by a display might be prompted by a number of requirements or factors: low power drain on batteries for a laptop or hand-held device, air conditioning needed to handle the heating from displays used in an enclosure, drain on power sources in a vehicle, etc. Unless you are able to access the power lines to the display these measurements will not be possible. In such cases manufacturing data may be the only source of information. Some displays require a backlight and manufacturers like to separate the power requirements of the light-valve matrix and associated electronics from the power requirements of the backlight. If the backlight is necessary for the task conditions, then its power should be included in the total power required to run the display. In complicated situations, all interested parties will have to agree on how to resolve any irregularities.

Another concern is for the range of power sources that are acceptable to the display for proper operation. Cost factors may be involved in the required accuracy of the power requirements. For this reason, there is a measurement included that verifies the operating range of the DUT.

14.1.1 POWER CONSUMPTION

ALIAS: power dissipation, total power

DESCRIPTION: We measure the power consumption of the DUT. **Units:** W (watt). **Symbol:** P .

CAUTION — EXCESSIVE VOLTAGE CAN DESTROY THE DISPLAY: When supplying power to any display from an external source over which you have control, always adjust the voltage to the manufacturer's specifications before connecting the display. If too much voltage is inadvertently applied, it can destroy the display.



Power Consumption is the total power used by the DUT for operation. It should be measured using a displayed video pattern that produces the greatest amount of current draw for the DUT from the applied voltage(s). The applied voltage should be well regulated and have sufficient current capability so that it does not change when the display current changes.

Many LCDs have inverters to power backlighting systems, and the power required for the backlight is part of the total display power, since the DUT will not be fully usable without its operation. Inverters convert dc voltage to ac to drive fluorescent lamps that produce the brightness for LCDs. That process produces conversion losses and causes additional power consumption that is not part of the actual display power consumption. The true power consumption for LCDs with backlights must include the total power as seen at the input of the inverter to be the total value. For inverter power measurements, the displayed video does not matter, since the inverter power consumption is non-video related. Note: in this version of the document, no recommendations are made to measure the power at the output of the inverter (the backlight input).

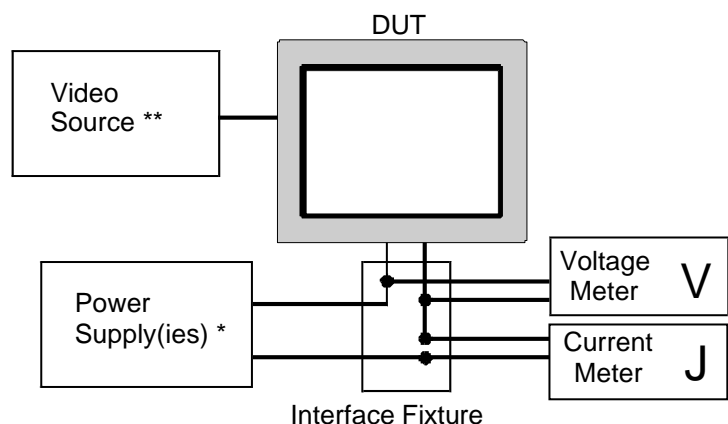
The total power consumption is the display power plus the inverter power (if applicable) or other backlight/projector lighting, and in some cases may include non-display related power, such as in monitors where the display supply voltage also supplies other circuits, such as USB or 1394 interfaces, or audio or non-display video circuits. In addition, some monitors may have ac voltage input, requiring ac/dc converters, which produce additional power due to their conversion loss inefficiencies. The power required for a backlight for an LCD or lighting systems to produce light for a reflecting or projector display, must always be included in the total power consumption.

Power is always additive, so the total power is the sum of all the individual powers, including the backlight with inverter (where applicable), the display or panel, and any other incidental power (such as USB, 1394, etc.) when the total power of a monitor which contains such circuits is desired.

NOTE: Power P is the product of the voltage V and current J : $P = V J$.

$$P = VJ \quad \begin{cases} P = \text{power in watts (W)} \\ V = \text{voltage in volts (V)} \\ J = \text{current in amps (A)} \end{cases}$$

(For ac the voltage and current would be the root-mean-square ["rms" or "RMS"] values.) If a direct power reading instrument is employed to make the power measurements, use its numbers directly without voltage and current measurement or calculations.



**Table 1. Power Consumption Display Conditions**

	Case 1	Case 2 (preferred)	Case 3	Case 4
	Embedded Display	Standalone FPD & Projector Engines	FP Monitor & Projection Systems	FP Monitor with additional circuits
Measure Power?	no *	yes **	yes	maybe (user option)

*Embedded system, such as for an enclosed laptop computer. For exception cases in which the display power can be measured, see text below.

**Case 2 is the preferred method of testing and should be used whenever possible.

NOTE: If the supply line is to be interrupted and the current measured in series with the power source, a special interface fixture may be needed to measure the current.

Table 2. Power Source Alternatives

	Case 1	Case 2	Case 3	Case 4	
Conditions	Embedded Display	Standalone FPDs & Projector Engines	FP Monitor & Projection Systems	FP Monitor ** with additional circuits	Comments
ac supply	--	no	maybe *	maybe *	Convert to RMS
dc supply	--	yes	yes	maybe **	
multiple dc supplies	--	yes	yes	maybe **	Sum all supplies

* Measurement of a monitor with ac input will include non-display-related losses due to the inefficiencies of the ac/dc conversion process. This assumes dc input to any DUT being measured. That is not part of the display power consumption directly, and it is up to the user if he/she chooses to include or exclude that.

**FPD monitors with additional (non-video-related) circuits may have the input power measured just as in Case 3, but the usefulness of the total power must be determined by the user.

Table 3. Backlight (or other luminance source) Options

	Case 1	Case 2	Case 3	Case 4	
Conditions	Embedded Display	Standalone FPDs & Projector Engines	FP Monitor * & Projection Systems	FP Monitor * with additional circuits	Comments
Backlight*	--	maybe	maybe	maybe	Add backlight power to total

*Backlights, or external luminance sources may be of several types. They may include a fluorescent-tube backlight, other types of backlights, such as LEDs or EL, or rear or reflected lamps, such as for projector applications.

Case 1: A DUT which is integrated in a system, in which the system supply powers both the system and the DUT, with no access to the power that goes directly to the DUT. An example would be an enclosed laptop computer. In this case, the display power usually cannot be determined and power consumption for the displays are not realizable. (*Note: Under special conditions, power for the DUT can be measured in an embedded system. These conditions would either entail disassembly of the system sufficiently to gain access to the voltage source to the DUT and inverter or entail knowledge of the total system power and being able to subtract that from the power of the display. It is up to the user to determine if such measurements are practical for his conditions.*)

Case 2: A standalone display (which will include an inverter for many LCDs), the total power is equal to P_{display} , or $P_{\text{display}} + P_{\text{inverter}}$ *, if the DUT has an inverter. Note that for displays which have multiple voltage supplies, such as +5V and +12V, that the power of all individual sources are added, such as $P_{\text{display}} = (P_{5V} + P_{12V} + P_{\text{inverter}})$. *Case 2 is the preferred method of testing and should be used whenever possible.*

Case 3a: A flat panel monitor which contains no circuitry other than for the DUT (perhaps with inverter) and is powered entirely by ac (line voltage) only. The total power of the DUT is the power read at the ac input. e.g. $P_{\text{display}} = P_{\text{ac}}$

Case 3b: A flat panel monitor that contains no circuitry other than the DUT (perhaps with inverter) and is powered by dc. The total power of the DUT is the power read at the dc input. e.g., $P_{\text{display}} = P_{\text{dc}}$. If there is more than one dc source, then add the individual powers of each, such as $P_{\text{display}} = P_{\text{dc1}} + P_{\text{dc2}} + \dots + P_{\text{dcn}} + P_{\text{inverter}}$.*

Case 4: A flat panel monitor which contains non-video related power-consuming circuits, such as USB, 1394, audio amplifier power, etc., and the total power of the monitor is to be considered, then the total power is equal to the sum of the individual powers. For example, total power $P_{\text{total}} = P_{\text{display}} + P_{\text{inverter}} + P_a + P_b + \dots + P_n$, where P_a, P_b, \dots, P_n , are the powers of each non-video circuit section, such as USB, 1394, audio power, etc.



Note: For Case 4, you must determine if measuring the DUT plus the other circuits in a monitor system is the most useful information for the specific power consumption evaluation, since the other power consumed is not actually part of the display power.

*This may be for inverter or other display lighting power. Eliminate the P_{inverter} term if the DUT has no inverter (or set it to be “0”) or lighting power circuits.

SETUP:

1. EQUIPMENT

Alternative 1: An ac-operated display (in which the ac powers the display only), e.g., might be found for Case 3 or Case 4.

- An ac power measurement test set which reads ac power directly, or P .
- Separate RMS voltage and current measurement equipment, or $P = V_{\text{rms}} J_{\text{rms}}$
- Peak-to-peak (p-p) voltage, current measurement equipment, for which $P = \frac{V_{\text{p-p}}}{2\sqrt{2}} \frac{J_{\text{p-p}}}{2\sqrt{2}}$
- Frequency of the ac voltage should also be recorded whenever ac is employed.

Alternative 2: An external display*, in which the display power source(s) is accessible independent of a system, and externally powered (generally by dc). e.g., Case 2, Case 1 with some disassembly, or might for Case 3.

- dc voltage meter
- dc current meter (It may be necessary to interrupt the supply or supplies and place the current meter in series with the supply). Note: A special interface fixture may be needed to accomplish this.
- Set voltages of external power supplies for the display rated voltage(s) $\pm 1\%$.
- Power Measurement (V_i and J_i are dc values and “inv” is inverter): $P = V_a J_a + V_b J_b + \dots + V_{\text{inv}} J_{\text{inv}}$.*

Note: Depending upon the display, this may involve one or more than one supplies for the display, and one or more for the backlight inverter. The total power is equal to the sum of each of the individual powers. **Note: Alternative 2 will provide the most accurate readings and is the preferred electrical setup method whenever possible.**

*With backlight where applicable, such as for many LCDs. It is included since the backlight is part of the total power consumed by the display. For cases with no inverter, delete this term.

2. SETUP PROCEDURE

- Connect voltage(s) to the display, inverter, and any other display-related circuits.

Set the voltage to its specified value as accurately as possible (goal: $< \pm 0.5\%$)

- Display video pattern that produces the worst-case power for the display.

If the user does not know in advance what that displayed pattern for worst case pattern may be, then it may be necessary to try various patterns while monitoring the current drawn by the display.

Note: If you intend to determine the frontal luminance efficiency ε (14.2.1) be sure to measure the power using a white full screen in addition to any other pattern that might be used.

- Measure the power for each supply and calculate the display power consumption as follows:

$$P_{\text{total}} = V_1 J_1 + V_2 J_2 + \dots + V_n J_n + V_{\text{inv}} J_{\text{inv}} = P_1 + P_2 + \dots + P_n + P_{\text{inv}},$$

where $V_1, V_2, \dots, V_n =$ All voltages applied to the display,
 $J_1, J_2, \dots, J_n =$ All currents to the display,
 $V_{\text{inv}}, J_{\text{inv}} =$ Backlight inverter voltage and current.

For displays which have no inverter, disregard the inverter power measurements (set to zero) and use display power only for the total power.

For displays which have multiple supply voltages (to the display only), then the power for each supply must be determined, and all added together to determine total power for the display. If the display has different power consumption for different video patterns for each supply, then a single pattern should be selected by the tester and used for all the power measurements. *Note that if the frontal luminance efficiency (14.2.1) is to be measured a white full screen is required in addition to any other pattern selected.*

When only line input can be measured, power can be determined by using ac power meters or by actual measurements of the voltage and current and multiplying them. The resultant power should always be in RMS.

For displays integrated into systems in which the power source provides power to other circuits in addition to the display, such as laptops or displays with additional internal circuits, and the power to the display cannot be isolated for measurement, then the power consumption may be difficult to determine. The user may want to not include power measurements in such cases.

**PROCEDURE:**

1. Adjust the power input for specified values, $\pm 1\%$ (goal $< \pm 0.5\%$).
2. Attach voltage and current measuring devices (or power measurement devices) to the input.
3. Display the desired pattern on the screen:
 - a) Worst case pattern: The pattern that causes the greatest amount of power consumption such as an alternating pixel pattern.
 - b) White screen: Display a full luminance, all white full-screen display (as in § 5.3 Full-Screen White).
4. Inverter (for displays that use an inverter to power a backlight):

Note: For measurement of inverter power for LCDs, power will not vary dependant on the displayed video.

 1. Apply the rated voltage input for specified value, $\pm 1\%$ (goal $< \pm 0.5\%$). This is V_{inv} or $V_{inverter}$.
 2. Set the inverter adjustment (if there is one) for maximum output (that is, maximum luminance).
 3. Measure the input current to the inverter. This is J_{inv} or $J_{inverter}$.
 4. Backlight (or inverter) power = $V_{inv} I_{inv}$.
5. Video Pattern: If luminance is important, measure the luminance at the front center of the screen, using standard measurement techniques (see § 5.3 Full-Screen White). If the frontal luminance efficiency (§ 14.2.1) is to be determined, then a full-screen white pattern must also be used in addition to any other pattern selected. If the frontal luminance efficiency is not to be determined, any video can be used that maximizes the power consumption.

ANALYSIS: Perform necessary calculations to fill in Table 4

REPORTING: Report the following on the reporting sheet: Video pattern used, input voltage (all), input current (all), input power (all), and the total power consumption

—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Table 4: Power Consumption Reporting - Sample Data				
Pattern Used:	1 pixel by 1 pixel alternating pixel pattern			
Input Supply	Volts, V (in V)	Current, I (in A)	Power, P (in W)*	
Panel	5.2	0.4	2.08	$P_{pan} = V_{pan} J_{pan}$
Inverter **	12.05	0.502	6.05	$P_{inv} = V_{inv} J_{inv}$ **
Total *	—	—	8.13	$P = P_{pan} + P_{inv}$ **

$$*Total\ Power = P_{display} + P_{inverter}^{**} + P_{other}^{**}$$

**If used

* Note: For additional voltage sources and their associated currents, report their values on comment sheet.

* If ac voltage is used, report the voltage frequency.

COMMENT: Display Modes: Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.



14.1.1.1 POWER FOR COLOR-SIGNAL WHITE

ALIAS: power for RGB white

DESCRIPTION: We measure the power consumption of the DUT using the nonatile-trisequence patterns. **Units:** cd/m²/W.

Symbol. P_{CSW} .

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See § 5.4 Color-Signal White for full details.

SETUP & PROCEDURE: Setup and procedures are found in 14.1.1 Power Consumption.

1. Arrange for three patterns to be displayed on the full screen as shown in Fig. 1, called the nonatile-trisequence patterns, which consist of saturated RGB rectangles in a 3x3 matrix that covers the screen.
2. Measure the power (using 14.1.1 Power Consumption) for each pattern: P_{NTSR} , P_{NTSG} , P_{NTSB} .

ANALYSIS: Calculate the power for color-signal white, P_{CSW} , where we consider two cases:

Case 1: For displays in which an extrinsic light source is the principal determinant of display light output and power consumption (e.g., projectors, LCD panels), power consumption is largely independent of the image displayed. Power should be calculated as follows:

$$P_{CSW} = (P_{NTSR} + P_{NTSG} + P_{NTSB})/3. \quad (1)$$

Case 2: For self-luminous displays in which display light output and power consumption are determined by light-emitting elements (e.g., OLEDs, plasma panels, CRTs), power consumption is directly proportional to the number of individual picture elements energized to display the image. Power should be calculated as follows:

$$P_{CSW} = (P_{NTSR} + P_{NTSG} + P_{NTSB}). \quad (2)$$

REPORTING: Report the power for color-signal white to no more than three significant figures.

COMMENTS: Display Modes: Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.

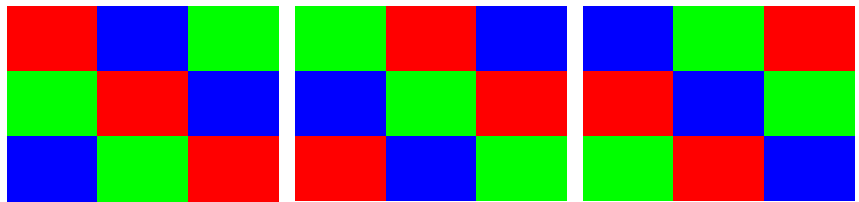


Fig. 1. Nonatile-trisequence patterns (NTSR, NTSG, NTSB, respectively).



14.1.2 POWER SUPPLY RANGE VERIFICATION

DESCRIPTION: This section provides guidelines on measuring the display operation over the specified voltage operating range. These measurements can only be made for any case in which the user can provide power for the isolated display or tap into the power on a display integrated into a system. It is assumed that the power to the display can be isolated and measured independently of supplying power to any non-display-related circuits. If the power is measured but also supplies other circuits, then the display power consumption reading may be useless.

It is considered that this test applies to dc power sources. Some technologies may have ac input, or it may be desired that the total power of the display including an ac source be tested. That may be done at the discretion of the user, but detailed information is beyond the scope of discussion in this test.

Note: Either perform this measurement before all other measurements or after all other measurements requiring display settings not to be changed. The adjustment of display controls calls for upsetting setup conditions that may be hard to reset accurately.

Caution: Care must be given to applying voltage(s). If an excessive voltage is applied it can destroy the panel.

Conditions to perform this test:

1. External, adjustable power supply is used (unless internal power supply can be adjusted over the specified operating range)
2. Power is isolated to supply the display and related circuitry (e.g., inverter) only.
3. An interface to apply the external voltage and measure the current.

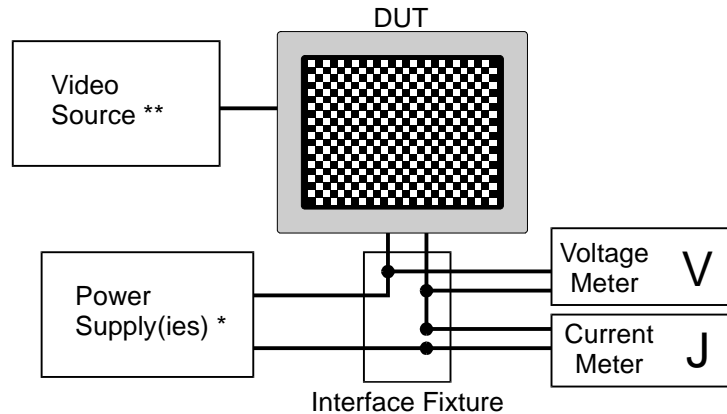


SETUP, PROCEDURE, & ANALYSIS: Using an adequate interface for supplying the voltage(s) and measuring the current, perform the following steps.

* **CAUTION:** Adjust and measure the voltage before applying it to the panel to avoid damage from excess voltage.

** **CAUTION** must be exercised to comply with any power sequencing issues with the display, such as sequence of applying voltage(s) and video, if necessary.

1. Apply a controlled voltage (or voltages) to the display.
2. Assure proper measurement equipment is used to determine the voltage and current, or power.
3. Display video content that is suitable to demonstrate worst-case power consumption by monitoring the supply current while changing video. (Note that the inverter power is independent of video content.)
4. Vary the voltage for each of the high, exact, and low settings, and measure the input voltage(s), current(s) and calculate the resulting input powers. Combine all power into a final total power consumption.



REPORTING: Report the following on the reporting sheet

- Input Voltage (all)
- Input Current (all)
- Input Power (all)
- Total Power Consumption
- Displayed video content (if practical)



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 1. Power Supply Range Reporting

Video Content (Pattern Used) | 2 pixel by 2 pixel checkerboard

Input Supply		Volts (V)	Current, I (A)	Power (W)*	
Panel	High	5.5	0.5	2.75	$P_{\text{panhigh}} = V_{\text{high}} J_{\text{high}}$
	Exact Value	5.0	0.5	2.5	$P_{\text{pan}} = V J$
	Low	4.5	0.5	2.25	$P_{\text{panlow}} = V_{\text{low}} J_{\text{low}}$
Inverter ***	High	12.5	0.6	7.5	$P_{\text{invhigh}} = V_{\text{high}} J_{\text{high}}$
	Exact Value	12	0.6	7.2	$P_{\text{inv}} = V J$
	Low	11.5	0.6	6.9	$P_{\text{invlow}} = V_{\text{low}} J_{\text{low}}$
Total Power **			High **	10.25	$P = P_{\text{panhigh}} + P_{\text{invhigh}} ***$
			Exact Value **	9.7	$P = P_{\text{pan}} + P_{\text{inv}} ***$
			Low **	9.15	$P = P_{\text{panlow}} + P_{\text{invlow}} ***$

*Power = $V \times I = V \cdot I = V I$ **Total Power = $P_{\text{display}} + P_{\text{inverter}} *** + P_{\text{other}} ***$

***If used

Note: For additional voltage sources and their associated currents, report their values on the comment sheet.

COMMENTS: None

14.2 EFFICIENCIES

The luminous efficacy (“efficiency”) of a display is the ratio of the light flux output for the entire display vs. the electrical power input to the display. This is often called the luminous efficiency but is more properly called the luminous efficacy and has been used for years in evaluating displays especially that exhibit a quasi-Lambertian light output like CRTs. (The CIE reserves the term “luminous efficiency” to mean the ratio of the luminous flux in lumens to the optical power [W] of the radiation.) However, some FPD technologies do not display a Lambertian-type of luminance distribution. Some displays produce no information output in certain directions but emit much light in those directions. Some displays are privacy displays that emit the information in a narrow solid angle along the normal (or other direction), but any light at larger angles from the normal contains no information. For these reasons some have felt that rating the display solely on the luminous efficacy is not always a good indicator of the effectiveness of the display in converting electrical power to light. To answer this need to provide a metric that enables an immediate evaluation of how much power is spent on producing the luminance the user will see, we offer the frontal luminance efficiency.

Recently, 2010, a new “efficiency” metric has been introduced that has been called “energy efficiency” and adopted as an evaluation criterion in certain countries. The most technically descriptive name would be “frontal intensity efficiency.” It is included in the end of this main section (§ 14.2.3).

Reflective displays: the luminance efficacy of a reflective display shall be measured as full-screen white at task specific ambient illuminance levels (as specified in chapter11).



14.2.1 FRONTAL LUMINANCE EFFICIENCY — ε

ALIAS: luminance to power ratio, luminance efficiency
[NOT luminous efficiency, NOT luminous efficacy]

DESCRIPTION: The frontal luminance efficiency is the ratio of the luminance to the driving power of the DUT. It is a simple calculation based on two other measurements: the electrical power to drive the display at full-screen white and the luminance of full-screen white. **Units:** $\text{cd}/\text{m}^2/\text{W}$. **Symbol:** ε .

The frontal luminance efficiency is an assessment of a display system's effectiveness of turning supplied electrical power input into the output luminance under normal viewing conditions. It is not an efficiency, per se, but it is similar conceptually, something out for something in.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in 14.1.1 Power Consumption where a full-white screen must be used to obtain the power measurement result P used here, and 5.3 Full-Screen White with a luminance result of L_W .

ANALYSIS: The frontal luminance efficiency ε is calculated from the measured input power P and the measured luminance full-screen-white luminance L_W given by

$$\varepsilon = L_W / P.$$

REPORTING:

Report the following on the reporting sheet: Input voltage, input current, input power, output luminance, and frontal luminance efficiency to no more than three significant figures each.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Reporting Frontal Luminance Efficiency (FLE) – Sample Data					
Input	Pattern Used	Full-screen white			
	Input Supply	Voltage, V (V)	Current, J (A)	Power, P (W)	Equation
	Panel Supply	3.32	1.36	4.50	$P_{\text{pan}} = VJ$
	Inverter Supply*	5.18	1.35	7.02	$P_{\text{inv}} = VJ^*$
	Total Power **			11.5	$P = P_{\text{pan}} + P_{\text{inv}}^{**}$
Output	Luminance, L (cd/m^2)	73.4			L
Result	FLE, ε ($\text{cd}/\text{m}^2/\text{W}$)	6.37			$\varepsilon = L/P$

* If used.

** Total power is sum of powers to the panel electronics, the inverter (if used) and other sources.

COMMENTS:

The frontal luminance efficiency of the power to light (luminance) conversion process generally takes into account all the system losses, giving a single numeric value that can be used as a figure of merit for a display as a system. Based upon the fact that it gives intuitively useful information on the amount of output (luminance) derived from an input power, it is perhaps the most useful of all display measurement parameters for correlating the effectiveness of variations within one display technology or for comparing display technologies. It also can be a valuable tool for understanding where weaknesses lie in a display system, and where improvements can be determined. For example, the frontal luminance efficiency of a backlit LCD can be affected by the efficiency of the inverter driving the backlight. Changing the inverter to one with a higher efficiency will improve the entire efficiency of the display proportionately.

There are display devices for which frontal luminance efficiency may not be valuable as a figure of merit, such as paper-like displays or reflective displays. Correlating such displays with those intended to produce luminance output from electrical power is beyond the scope of this section. However, if we were to conceive of a comparative metric for reflective displays, we might judge reflective displays on a common ground based on task conditions. The luminance of the reflective display would have to be judged on the basis of the task illuminance.



14.2.1.1 FRONTAL LUMINANCE EFFICIENCY OF COLOR-SIGNAL WHITE — ϵ_{CSW}

DESCRIPTION: We calculate the frontal luminous efficiency of a display based on measurements of the luminance obtained from only the color-signal primaries L_{CSW} in 5.4 Color-Signal White and the power P_{CSW} as measured in § 14.1.1.1 Power for Color-Signal White. **Units:** cd/m²/W. **Symbol.** ϵ_{CSW} .

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for specific details of application.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in § 14.1.1.1 Power for Color-Signal White to obtain the power P_{CSW} and (2) 9.12 Luminous Flux for Color-Signal White with a luminance result of L_{CSW} .

ANALYSIS: Calculate the frontal luminance efficiency of color-signal white, ϵ_{CSW} :

$$\epsilon_{CSW} = L_{CSW}/P_{CSW}.$$

REPORTING: Report the frontal luminance efficiency of color-signal white to no more than three significant figures.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the frontal luminance efficiency for color-signal white cannot be determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for comments.

My nit is bigger
than yours!





14.2.2 LUMINOUS EFFICACY (OF A SOURCE) — η

ALIAS: luminous efficiency

DESCRIPTION: We calculate the luminous efficacy of a full-white screen based on measurements of the luminous flux Φ in 9.11 Luminous Flux and the power P in 14.1.1 Power Consumption. **Units:** lm/W. **Symbol.** η .

The luminous efficacy can be somewhat misleading when applied to some FPD technologies that don't provide useful information in all directions.

APPLICATION: Emissive displays.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in (1) 14.1.1 Power Consumption where a full-white screen must be used to obtain the power measurement result P used here, and (2) 9.11 Luminous Flux with a flux result of Φ .

ANALYSIS: Calculate the luminous efficacy from the input power P and the luminous flux Φ :

$$\eta = \Phi/P.$$

REPORTING: Report the luminous efficacy to no more than three significant figures. Include the luminous flux and the power if they are not otherwise reported.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the luminous efficacy cannot be determined.

14.2.2.1 LUMINOUS EFFICACY FOR COLOR-SIGNAL WHITE — η_{CSW}

ALIAS: luminous efficiency for RGB white

DESCRIPTION: We calculate the luminous efficacy of a full-white screen based on measurements of the luminous flux obtained from the color-signal primaries Φ_{CSW} in 9.12 Luminous Flux for Color-Signal White and the power P_{CSW} in § 14.1.1.1 Power for Color-Signal White. **Units:** lm/W. **Symbol.** η_{CSW} .

The luminous efficacy can be somewhat misleading when applied to some FPD technologies that don't provide useful information in all directions.

APPLICATION: Emissive displays.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in § 14.1.1.1 Power for Color-Signal White and (2) 9.12 Luminous Flux for Color-Signal White with a flux result of Φ_{CSW} .

ANALYSIS: Calculate the luminous efficacy from the input power P_{CSW} and the luminous flux Φ_{CSW} :

$$\eta_{\text{CSW}} = \Phi_{\text{CSW}} / P_{\text{CSW}}.$$

REPORTING: Report the luminous efficacy for color-signal white to no more than three significant figures. Include the luminous flux for color-signal white and the power if they are not otherwise reported.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the luminous efficacy for color-signal white cannot be determined.



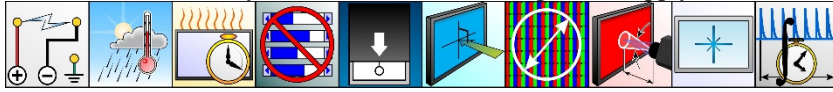
14.2.3 FRONTAL INTENSITY EFFICIENCY (“ENERGY EFFICIENCY”) — ξ

ALIAS: China’s energy efficiency

DESCRIPTION: The frontal intensity efficiency $\xi = L_W S / P$ is a calculation of the ratio of the luminous intensity I measured at the normal to the power consumption P . Some have called this “energy efficiency.” This luminous intensity is an approximate value; it is defined as the product of the frontal luminance L_W of the white full screen and the area S of the screen $I = L_S$.

Units: cd/W. **Symbol:** ξ .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Referring to the drawing... plug them in! ☺

PROCEDURE:

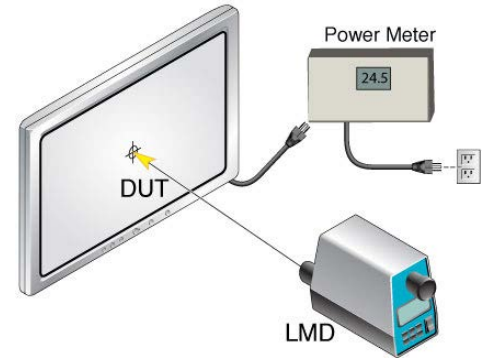
- Determine the area of the display in appropriate units, square meters (m^2) if you are measuring luminance in cd/m^2 (as specified in this document).
 - It is up to the tester to determine the area of the display. For fixed pixel displays you can calculate the area as follows: Given the diagonal size in inches, D_{in} , or meters, D_m , and the pixel array, $N_H \times N_V$, we have: $D_m = D_{in} \times 0.0254$ m/in. The area is: $S = \sqrt{\frac{D_m^2 N_H^2}{N_H^2 + N_V^2}} \times \sqrt{\frac{D_m^2 N_V^2}{N_H^2 + N_V^2}}$.
 - For displays that do not have fixed pixel arrays (e.g. variable raster displays like CRTs), calculate the area based on the inside edges of the bezel, within 1% of the bezel edges, and based on the designed aspect ratio of the display.
- Measure the luminance L_W for full screen white or maximum level where no luminance loading occurs.
- For the maximum luminance condition of step 2, measure the power P of the display. The power must be measured within 1 minute from the time that the luminance was measured.

ANALYSIS: The display frontal intensity efficiency or “energy efficiency” is:

$$\xi = L_W S / P \quad (1).$$

REPORTING: Report the following on the reporting sheet: active area of the display, output luminance, power, and efficiency to no more than three significant figures each.

COMMENTS: (1) **Pattern Conditions:** Use full screen for white levels if no luminance loading occurs. For displays with luminance loading assure that the white is at the maximum luminance. (2) **Similarities:** This metric is very similar to the frontal luminance efficiency metric except that it scales based on the area of the display.



—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Analysis Example:			
Item	Variable	Value	Unit
Area	S	0.1404	m^2
Luminance	L_W	214	cd/m^2
Power	P	24.5	W
Efficiency	ξ	1.293	cd/W



14.2.3.1 FRONTAL INTENSITY EFFICIENCY OF COLOR-SIGNAL WHITE — ξ_{CSW}

DESCRIPTION: We calculate the frontal intensity efficiency of a full-white screen based on measurements of the luminance obtained from only the color-signal primaries L_{CSW} in 5.4 Color-Signal White, the power P_{CSW} as measured in § 14.1.1.1 Power for Color-Signal White and the area S of the screen as determined in the previous method § 14.2.3 Frontal Intensity Efficiency ("Energy Efficiency"). **Units:** cd//W. **Symbol.** ξ_{CSW} .

APPLICATION: For color displays in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for specific details of application.

SETUP: None, this is a calculation.

PROCEDURE: Procedures are found in § 14.1.1.1 Power for Color-Signal White to obtain the power P_{CSW} , (2) 9.12 Luminous Flux for Color-Signal White with a luminance result of L_{CSW} , and the previous method § 14.2.3 Frontal Intensity Efficiency ("Energy Efficiency").

ANALYSIS: Calculate the frontal intensity efficiency of color-signal white, ξ_{CSW} :

$$\xi_{CSW} = L_{CSW} S / P_{CSW}.$$

REPORTING: Report the frontal luminance efficiency of color-signal white to no more than three significant figures.

COMMENTS: If the power cannot be measured appropriately and cannot otherwise be adequately secured, then the this metric for color-signal white cannot be determined. See sections 5.4 Color-Signal White and § 14.1.1.1 Power for Color-Signal White for comments.



15. FRONT PROJECTOR MEASUREMENTS

We consider the measurement of front projectors and front-projection screens in this section. Often, illuminance measurements are performed on such projectors. We speak of illuminance measurements throughout this section, whereas we could equivalently consider irradiance measurements instead—the reasoning is the same. Illuminance meter uncertainty performance and uncertainty requirements may be found in the Metrology Appendix (A1 Light-Measuring Devices [LMDs] — Detectors). We add some preliminary remarks regarding measurement of projectors. It is important to note that like many metrics throughout this document, the measurements in this chapter can be highly sensitive to the mode setting of the projector, see § 2.1 Display Description, Identification, & Modes and § 3.2 Controls Unchanged and Modes for details regarding mode settings and recording.



15.1 STRAY LIGHT IN PROJECTION MEASUREMENTS

Stray light can affect front projection measurement usually more seriously than many anticipate. Some use black screens in black rooms to reduce the stray light—a good idea. However, making a checkerboard-contrast measurement in such a room can still result in errors of several tens of percent in the measurement of black because of stray light from the room—yes, even with a black screen and a black room! Additionally, when hand-held illuminance meters are used, care must be taken that the clothing and hand of the person holding the illuminance meter does not reflect light onto the illuminance detector surface.

15.1.1 DARKROOM REQUIREMENTS

We don't invoke a minimum illuminance for front-projector measurements. Even with black walls, a black screen, and careful control of any instrument lights (including computers), a projection room is not completely dark. Reflections of light off the screen (even if black) will bounce off the walls and apparatus to contaminate the illumination falling on the screen from the projector. Yes, it is always better to use a darkroom with a black screen, but that will not always be possible. Thus, rather than strictly requiring stray-light illumination to be below some minimum, we can attempt to make corrections for stray light as needed. The use of a black screen with stray-light corrections can even permit the use of a room with white walls. Thus, it is better to measure the stray-light contamination and account for it rather than trying to eliminate it by fixing room conditions.

15.1.2 PROJECTOR PLACEMENT

The placement of the projector relative to the screen should be detailed in the manufacturer's specifications. Often the lens axis of the projector will be orthogonal to the vertical line at the center of the screen and placed either at a level near the bottom or above the screen. The image plane is usually vertical, parallel to the x - y plane. The projector is usually placed on or attached to a horizontal surface parallel to the x - z plane. See Figure 1. It is worth noting that the relative amount of flux exiting the lens of the front projection can be affected by the focus and zoom of the projector lens. There may be an optimum distance from the screen where the flux is greatest. Manufacturing specifications should provide guidance on this optimal distance and zoom.

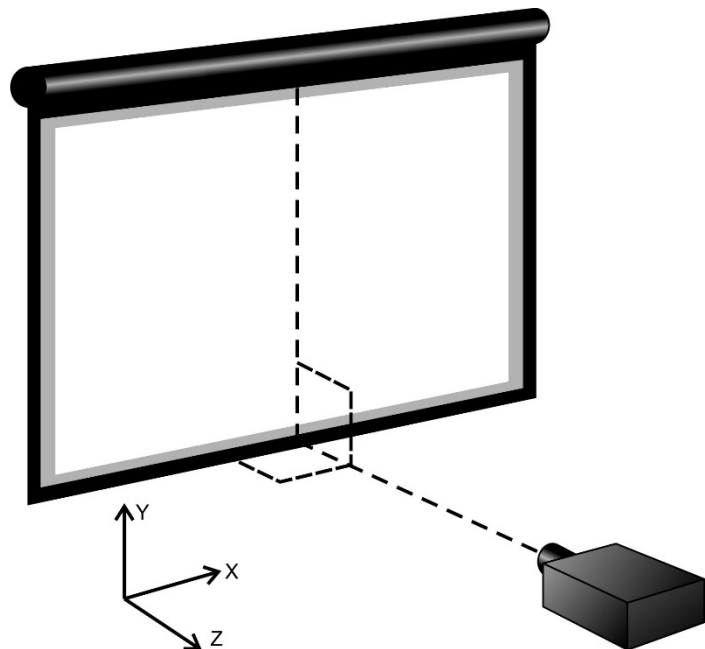


Fig. 1. Projector placement.



15.1.3 VIRTUAL SCREEN

A virtual screen is a vertical plane in space where the projected image would be focused if a projection screen were placed in that plane. Instruments to measure the light are often placed within and behind the framework so that their detector inputs are along the image plane. See Figure 2.

One way to provide a virtual screen is to construct a black framework to define a surface with black material provided behind the framework to reduce scattered light into the room. The face of the framework defines the virtual screen surface. Millimeter grids can be accurately placed in the corners of the framework in such a way as to permit an accurate measurement of the location of the corners of the projected image. The desired accuracy of the placement of the grids to define the projected image in this way is 0.2 % or less of the minimum of the horizontal and vertical size of the projected image; for a projected area of $1.333 \text{ m} \times 1 \text{ m}$ this requires a grid placement accuracy of 2 mm or less.

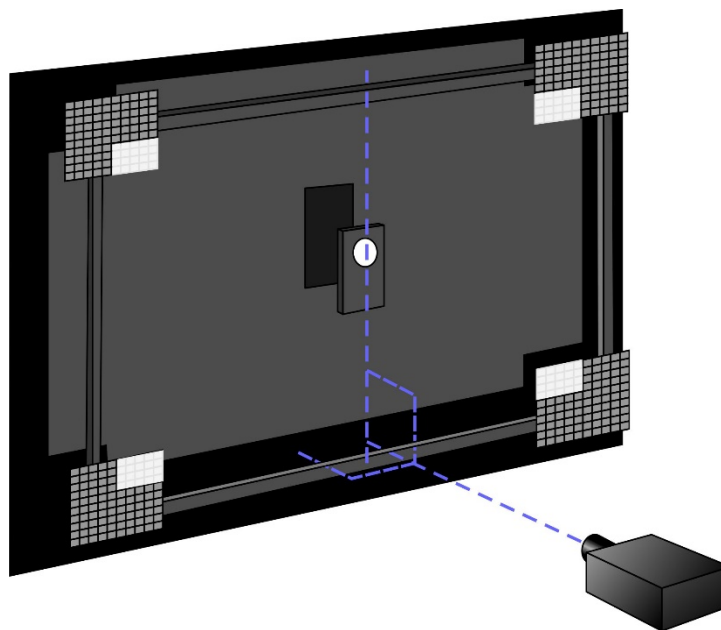


Fig. 2. Virtual screen with black background.

15.1.4 PROJECTION MASK

Projection masks permit the determination of the stray-light corruption of projection measurements made in darkened rooms. A projection mask is a thin matte-black disk from 1.5 to 3 times the diameter of the acceptance area diameter of the detector. The projection mask is used to shadow the detector from the direct rays from the projector and is placed from 30 cm to 60 cm in front of the detector—the larger projection masks being placed at a greater distance from the detector. With the projection mask in place, the detector output is a measure of the stray-light contamination from the room and can be different for each pattern displayed. Black screens and a darkened room are preferred. See Figure 3. If a black screen is not readily available, then a darkened room will suffice. However, the projection mask has been found not to work particularly well in bright rooms such as bright conference rooms.

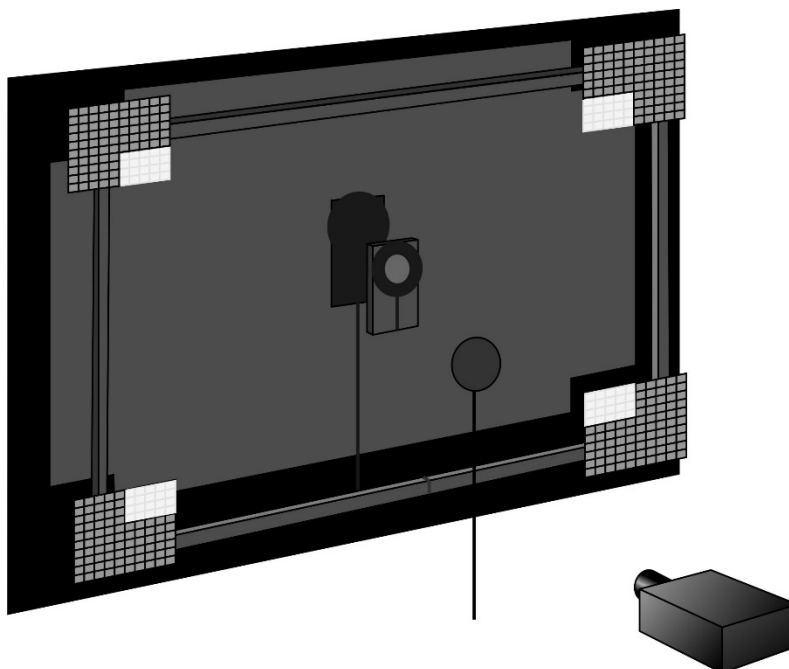


Fig. 3. Projection mask in darkened room for stray-light measurement.

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



15.1.5 SLET—STRAY LIGHT ELIMINATION TUBE

Stray-light-elimination tubes (SLETs) permit the measurement of the projected illuminance by rejecting stray-light corruption even in well-lit rooms—see Figure 4. A SLET is useful for attempting front projector measurements even in a fairly well-lit room. The disadvantage in our use of a SLET is having to aim the SLET directly at the projector and having to make cosine corrections in the resulting illuminance measurement for alignments that are not normal to the screen.

One version of a SLET is constructed with five frusta: Four are in pairs back-to-back, and one is at the end to prevent light scattering off the illuminance meter from reflecting back to the illuminance meter and corrupting the measurement. The entry frustum has a slightly smaller inner diameter than the next three frusta so that the light from the projector doesn't illuminate the inner diameters of the second set of frusta—if at all possible. The interior of the tube and the frusta are all gloss black. The idea is to control the stray light to virtual extinction by multiple reflections rather than trying to diffusely absorb it. For clarity the interior of the tube is not shown in the bottom of Figure 4.

If the SLET is constructed so that the illuminance meter must be tilted in the direction of the projector so that the illuminance meter is flat against the back of the SLET, then an angular correction must be made to the resulting measurement, E_{SLET} , if it is required that the illuminance measurement, E , be made parallel with the image plane:

$$E = E_{\text{SLET}} \cos \theta, \quad (1)$$

where θ is the angle from the normal of the image plane. Simpler versions of the SLET offer only three or even two interior frusta along the tube with a corresponding possible increase in the admission of stray light. By sighting up the SLET from the illuminance meter position using your eye, it is possible to inspect for stray-light entering the SLET. Judicious placement of the frusta can virtually eliminate the stray light from the room.

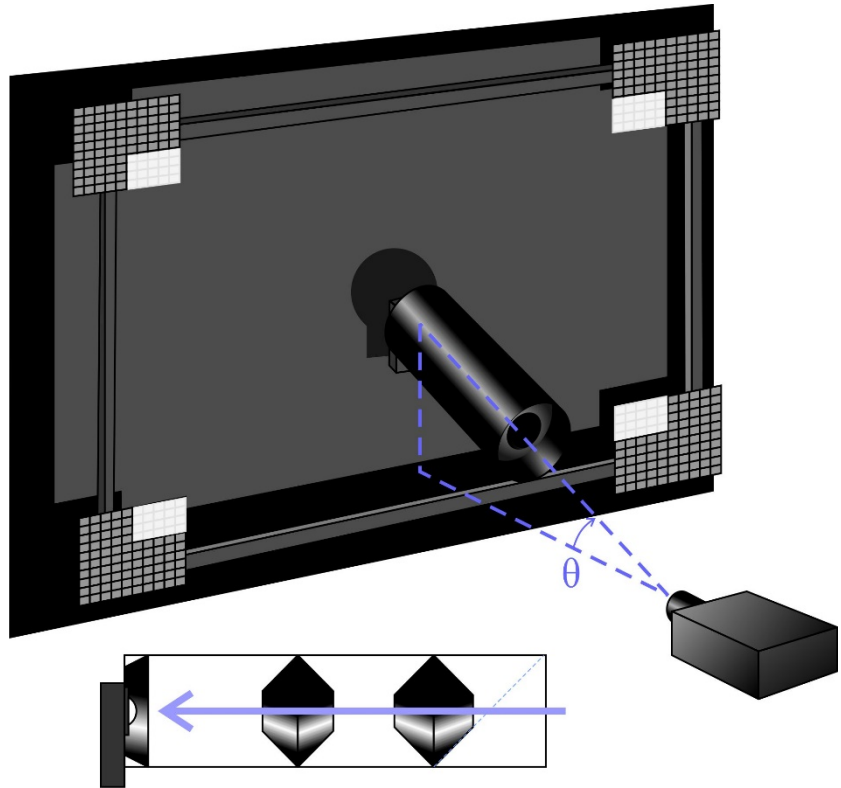


Fig. 4. Stray-light-elimination tube (SLET) with a cutaway showing five interior frusta. In the bottom cutaway the illuminance meter is on the left and the light from the projector comes from the right (bluish line).



15.1.6 PROJECTION LINE MASK

One way to establish a line contrast for a front projector is to use a black line that casts a shadow the same size as the projected black line width. The amount of light falling on the shadow is an indication of the correction that needs to be made to the white-line luminance and black-line luminance. The method proceeds as depicted in the figure below.

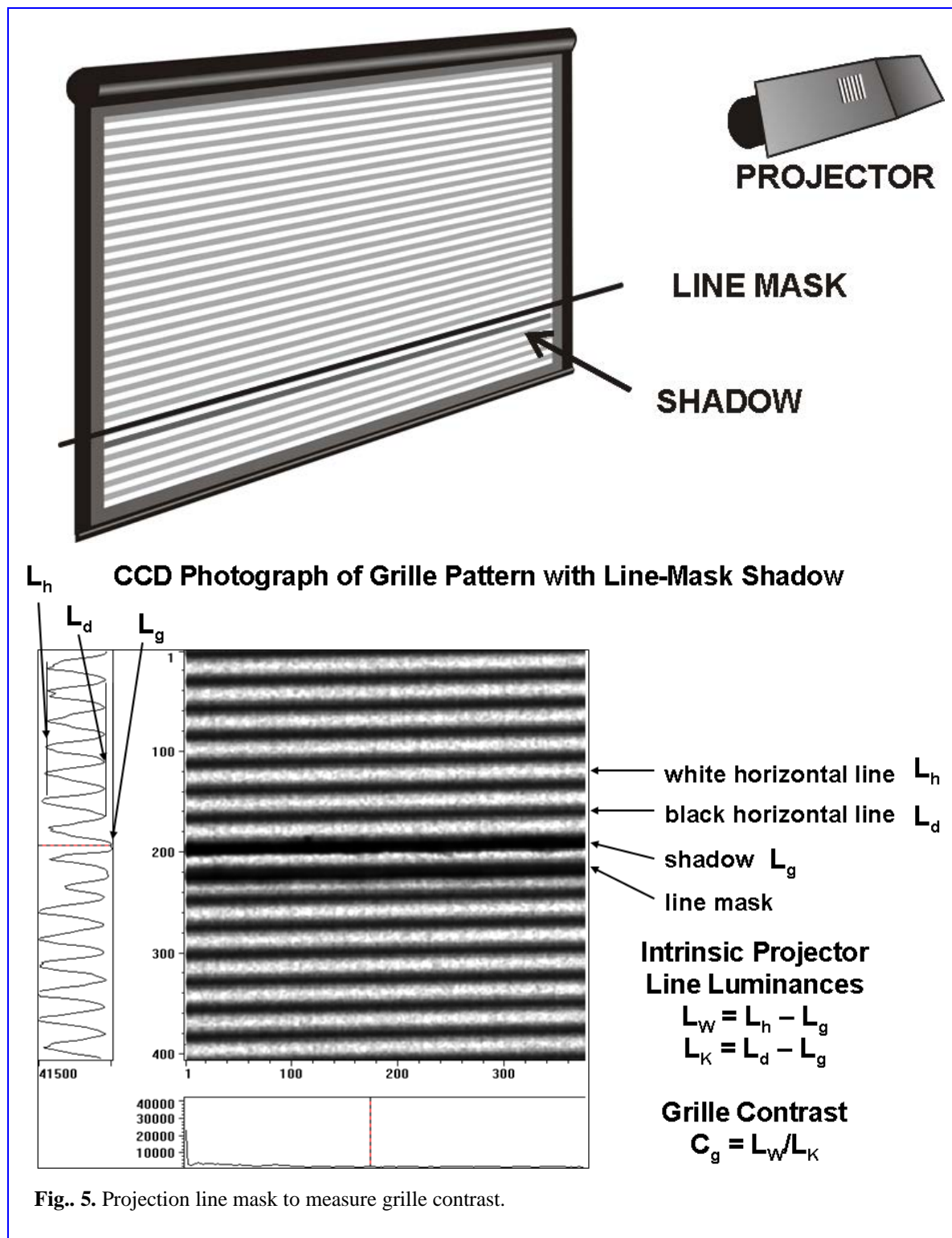


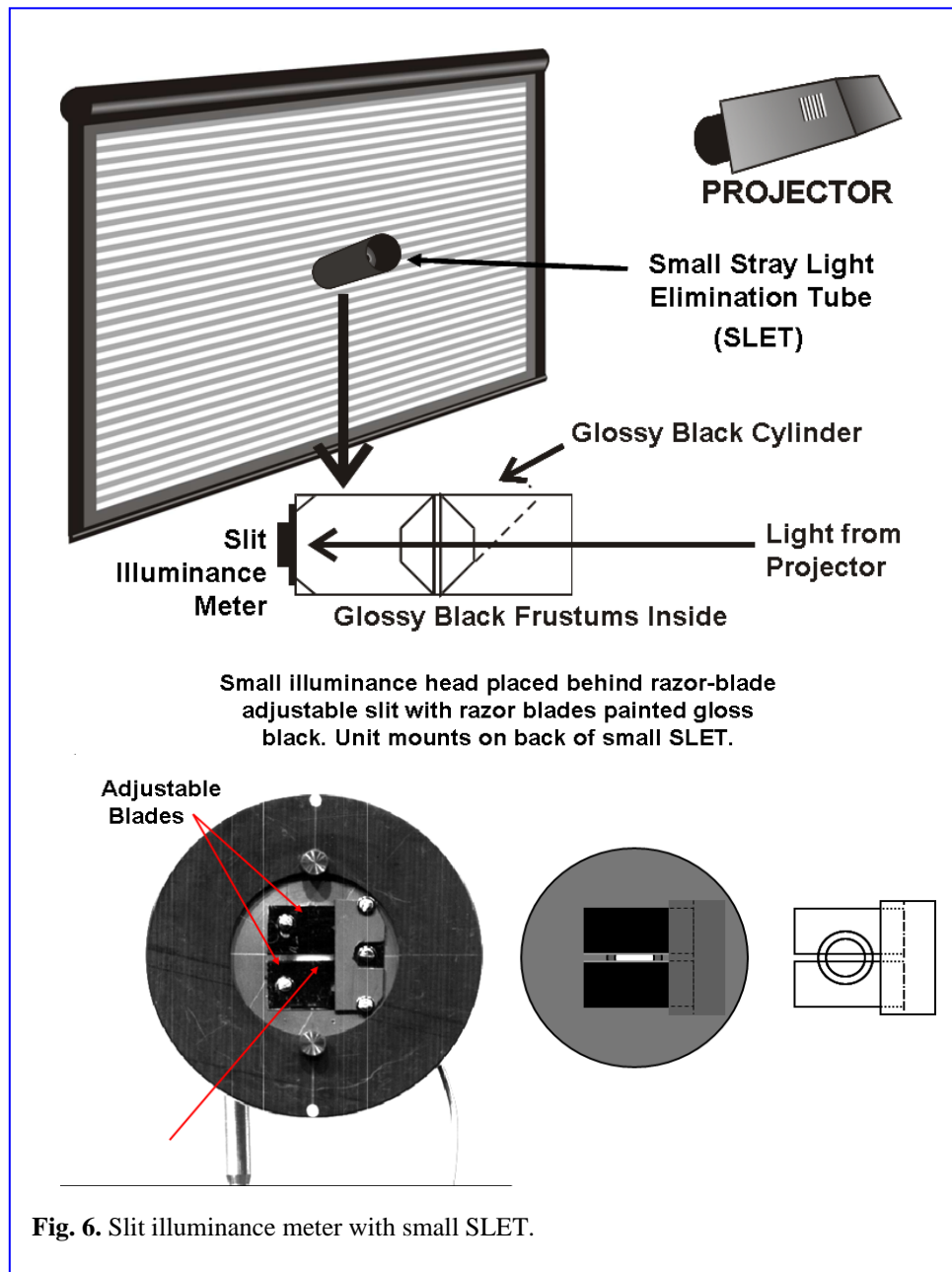
Fig.. 5. Projection line mask to measure grille contrast.



15.1.7 PROJECTION SLIT ILLUMINANCE METER

Another method to measure a projected line luminance is with the use of a slit illuminance meter. Two blackened razor blades are mounted in front of a small illuminance head. The slit width is adjusted to be somewhat smaller than the thickness of the line being measured, which helps avoid slight misalignment problems. If only contrast measurements are needed, then this detector does not need to be calibrated. To eliminate stray light, we will need a stray-light-elimination tube (SLET). Sometimes, if the room is dark, a simple SLET can work well. This will provide a direct relative measurement of the white and black lines without the need to make stray light corrections. If an absolute calibration is needed, the measurement result from the slit illuminance meter can be compared to a normal illuminance measurement result with the use of a white area of the screen where there are no black lines.

As with the larger SLET, if the illuminance meter must be tilted by angle θ out of the plane of the screen, then an angular correction must be made to the resulting measurement, E_{SLET} , whenever it is required that the illuminance measurement, E , be made parallel with the image plane: $E = E_{\text{SLET}} \cos \theta$.





15.1.8 ILLUMINANCE FROM WHITE REFLECTANCE STANDARDS

White reflectance standards (we will refer to them as pucks here) are often made from sintering powdered material into a disk shape. Often their hemispherical diffuse reflectances are from $\rho = 0.98$ to over 0.99. Rather than the use of an illuminance meter, some have placed these pucks in the image plane and measured their luminance L in order to determine the illuminance E via

$$E = \frac{\pi L}{\rho} . \quad (1)$$

Strictly speaking this will *not* provide the correct illuminance. The use of a diffuse reflectance value of, say, $\rho = 0.99$ in Eq. (1) is true *only* for uniform hemispherical illumination. In general, it is *not* correct to use this relationship for the luminance meter and projector at various angles from the normal of the puck. These pucks are not perfectly Lambertian, as the use of Eq. (1) with the hemispherical reflectance would suppose.

To use such a puck to determine the illuminance, the puck would have to be calibrated for the geometrical configuration in which it is used. For projection systems the reflectance factor $R(\theta_s, \phi_s, \theta_d, \phi_d)$ would be required, where the source (projector) is at angles (θ_s, ϕ_s) relative to the normal of the puck and the detector (luminance meter) is at angles (θ_d, ϕ_d) relative to the normal—see the figure. Changing any of those angles can significantly change the value of the reflectance factor. Therefore, the correct relationship is

$$E(\theta_s, \phi_s) = \frac{\pi L(\theta_s, \phi_s, \theta_d, \phi_d)}{R(\theta_s, \phi_s, \theta_d, \phi_d)} , \quad (2)$$

where the reflectance factor calibration properly accounts for the source and detector angles employed. Depending upon the angles used, the error in using Eq. (1) can be as much as 10 % or larger.

For measuring full-screen contrasts the pucks can be useful, but only with the luminance meter, the projector, and the puck at the same location for each measurement. Under such full-screen-contrast measurement conditions, the expression for the contrast,

$$C = \frac{L_W}{L_K} , \quad (3)$$

holds true, where L_W and L_K are the luminance measurements using the puck at center screen. This assumes that the stray light in the room comes only from back reflections from the screen illumination and not from various sources of stray light, such as instrumentation lights or computer screens. It also assumes that the patterns are full-screen white or black so that there would be no stray-light problems with the detector.

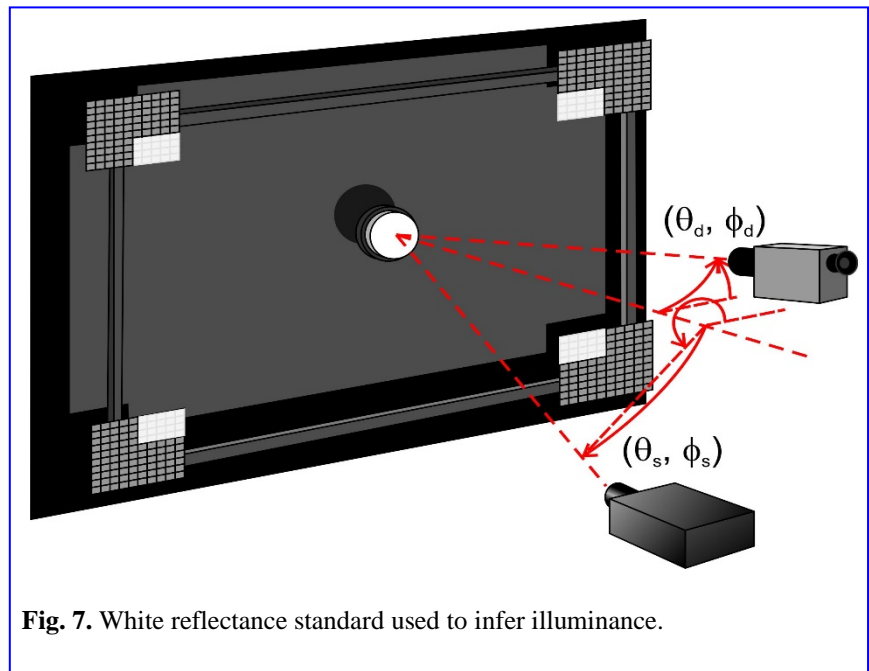


Fig. 7. White reflectance standard used to infer illuminance.

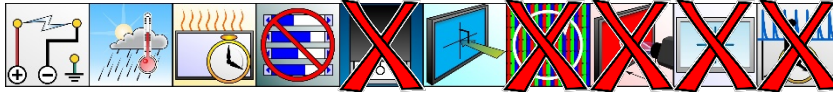


15.2 AREA OF FRONT PROJECTOR SCREEN IMAGE

DESCRIPTION: We measure the rectangular or quadrilateral area of a projected image from a front projector displaying a white pattern on a front-projection screen. **Unit:** m². **Symbol:** A.

APPLICATION: Front projectors.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: (1) The front-projection screen used (virtual or real) must provide a means to determine the location of the corners of the projected image to within a distance of 0.2 % of the minimum of the horizontal or vertical projected image size. (2) A native-resolution full-screen white pattern is required (pattern FW*.* or equivalent). (3) It is preferable that the projected image have an area of no less than 1 m². (4) Some projectors provide trapezoidal adjustments, but the image does not have to be perfectly rectangular to determine its area. A quality video generator is strongly recommended.

PROCEDURE: The procedure depends on whether or not the projected image is rectangular:

Rectangular Image: If the projected white image corners define a rectangle, then make a straightforward measurement of the horizontal dimension H and vertical dimension V of the image.

Nonrectangular Image: If the projected white image is *not* sufficiently rectangular, then determine the horizontal (p_x, q_x) and vertical components (p_y, q_y) of the diagonals of the projected white image (Figure 1): $\mathbf{p} = p_x \mathbf{e}_x + p_y \mathbf{e}_y$, and $\mathbf{q} = q_x \mathbf{e}_x + q_y \mathbf{e}_y$, where \mathbf{e}_x and \mathbf{e}_y are unit vectors in the horizontal and vertical direction, respectively. The measurement will require an accurate grid to locate the corners of the projected image. (If a virtual screen is used, then grid plates must be accurately placed in the corners of the framework.) Determine the (x, y) coordinates of the corners of the projected image. Our notation will be: Lower left is (x_{LL}, y_{LL}) , lower right is (x_{LR}, y_{LR}) , upper left is (x_{UL}, y_{UL}) , and upper right is (x_{UR}, y_{UR}) .

ANALYSIS: If the projected white image is rectangular, then the area of the screen is given simply by the product

$$A = H V. \quad (1)$$

If the projected white image is not rectangular, then the components of the diagonals are given by

$$\begin{aligned} p_x &= x_{UL} - x_{LR}, & p_y &= y_{UL} - y_{LR} \\ q_x &= x_{UR} - x_{LL}, & q_y &= y_{UR} - y_{LL} \end{aligned} \quad (2)$$

Note that in Figure 1, q_x is negative. The area is then given by

$$A = \frac{1}{2} |\mathbf{p} \times \mathbf{q}| = \frac{1}{2} |p_x q_y - p_y q_x|. \quad (3)$$

REPORTING: Report the area in square meters as needed.

COMMENTS: This method assumes that the edges of the projected image are straight lines. See § 13.3.4 Large-Area Distortions for measurements of barrel and pincushion distortions. A reference for measuring a convex quadrilateral area is <http://mathworld.wolfram.com/Quadrilateral.html>.

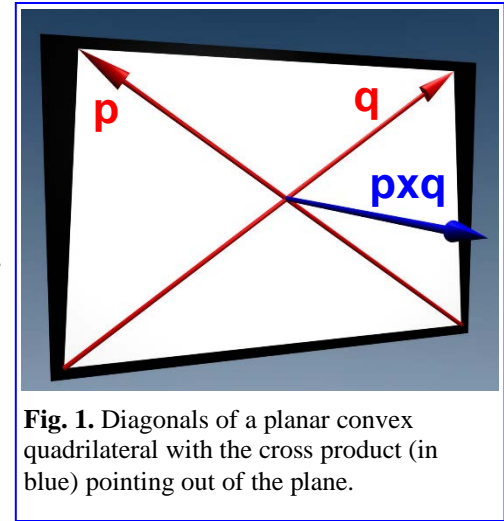


Fig. 1. Diagonals of a planar convex quadrilateral with the cross product (in blue) pointing out of the plane.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Nonrectangular Analysis and Reporting Example:
(Virtual screen with corner grids with origin at the lower left corner)

Corner	x (mm)	y (mm)
LL	-11	5
UR	1321	1000
LR	1307	13
UL	-18	997
$(p_x, p_y) =$	-1.325 m	0.984 m
$(q_x, q_y) =$	1.332 m	0.995 m
$A =$	1.315 m ²	



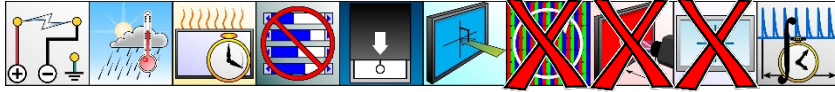
15.3 SAMPLED FLUX FROM WHITE

ALIAS: light output

DESCRIPTION: We calculate the luminous flux from a front projector by use of sampled illuminance measurements of a white full screen and the area of the projected image. **Unit:** lumen (lm). **Symbol:** Φ_W .

APPLICATION: Front projectors.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The illuminance measurements must be made in a room where the stray light is ignorable or can be accounted for as a correction. Patterns needed: (1) SET01S50 as in Figure 1, (2) AT02P to locate the centers of the 3x3 array of equal rectangles that defines the measurement grid (Figure 2), (3) FW or a full-screen white pattern. A video generator that uses the native resolution of the projector is strongly recommended.

PROCEDURE: Select the mode of operation of the projector to be measured. For each mode selected perform the following steps:

1. Measure the area A of the projected image according to § 15.2.
2. If possible, by adjustment of the projector settings, ensure that all the central dark gray and light gray levels in pattern SET01S50 (Figure 1) are discernable. Report any noncompliance.
3. Assure that the illuminance measurements are made at the nine centers of 3x3 equal (± 2 px) rectangles to within a radius of 2.5 % of the minimum of the screen height or width; this is the measurement grid. The use of a pattern as in Figure 2 (AT02P) can be helpful in determining the correct measurement locations.
4. Measure and record the illuminance of a full-screen-white projected image at the nine locations of the measurement grid.

ANALYSIS: We use the matrix notation i, j , where $ij = 11$ is the upper left and $ij = 33$ is the lower right, to define the locations of the measurement grid; i = row, j = column. The flux Φ_W is given by the product of the projected area and the average illuminance:

$$\Phi_W = AE_{ave} = \frac{A}{9} \sum_{i,j=1}^3 E_{ij} \quad (1)$$

REPORTING: Report the flux Φ_W to no more than three significant figures (unless more can be justified by an uncertainty analysis).

COMMENTS: This measurement method is an adaptation of *Electronic projection - Measurement and documentation of key performance criteria - Part 1: Fixed resolution projectors*, International Electrotechnical Commission, IEC 61947-1:2002(E), 40 pages, first edition 2002-08.



Fig. 1. Pattern (SET01S50) to set up the front-projector.

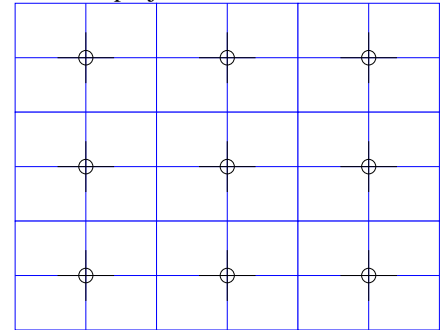


Fig. 2. Pattern (AT02P) to determine detector positions.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Analysis Example:					
Illuminance at each location:	$E_{11} =$	1732.0	$E_{12} =$	1828.4	$E_{13} =$ 1670.7
	$E_{21} =$	1868.0	$E_{22} =$	1972.6	$E_{23} =$ 1792.2
	$E_{31} =$	1902.4	$E_{32} =$	2022.2	$E_{33} =$ 1840.1
Average:	$E_{ave} =$	1847.6	Area, $A =$	1.116	m ² (from § 15.2)
Flux $\Phi_W =$		2061.9 lm			

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting Example		
Flux $\Phi_W =$	2060	lm



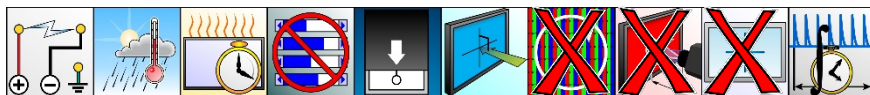
15.4 SAMPLED FLUX FROM COLOR-SIGNAL WHITE

ALIAS: color output, color light output

DESCRIPTION: We calculate the luminous flux from a front projector by use of sampled illuminance measurements of RGB primary colors using the nonatile, tri-sequence patterns. **Unit:** lumen (lm). **Symbol:** Φ_{CSW} .

APPLICATION: For color front projectors in which the input signals conform to a standard set of RGB voltages or digital values and for which departures from additivity of the color-signal primaries have been determined. See § 5.4 Color-Signal White for full details.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The illuminance measurements must be made in a room where the stray light is ignorable or can be accounted for as a correction. Patterns needed: (1) SET01S50 as in Figure 1, (2) AT02P to locate the centers of the 3x3 array of equal rectangles that defines the measurement grid (Figure 2), and (3) nonatile tri-sequence patterns (NTSR, NTSG, NTSB) consisting of three separate patterns with RGB 3x3 arrays (Figure 3). A video pattern generator is strongly recommended for the nonatile tri-sequence patterns in the native resolution of the projector.

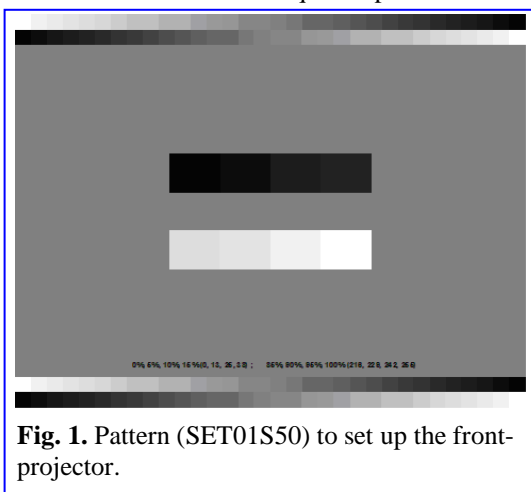


Fig. 1. Pattern (SET01S50) to set up the front-projector.

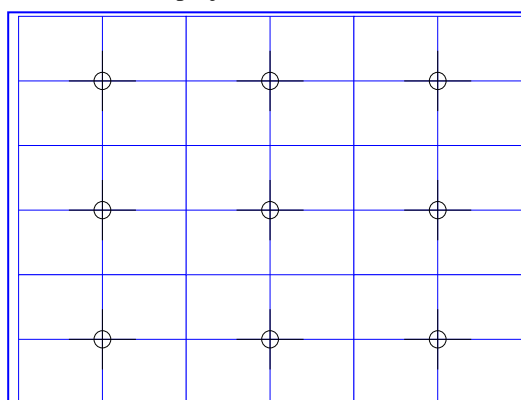


Fig. 2. Pattern (AT02P) to determine detector positions.

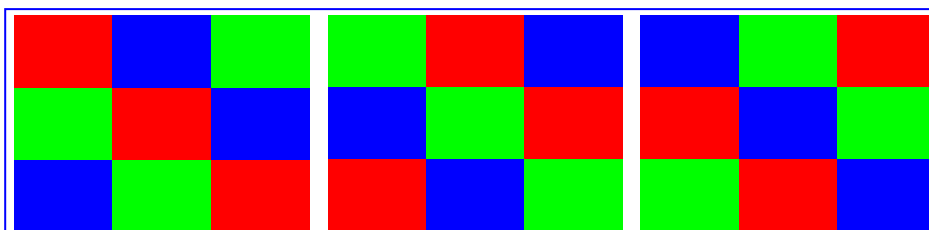


Fig. 3. Nonatile tri-sequence patterns (NTSR, NTSG, NTSB, respectively).

PROCEDURE: Select the mode of operation of the projector to be measured. For each mode selected perform the following steps:

1. Measure the area A of the projected image according to § 15.2.
2. If possible, by adjustment of the projector settings, ensure that all the central dark gray and light gray levels in pattern SET01S50 (Figure 1) are discernable. Report any noncompliance.
3. Assure that the illuminance measurements are made at the nine centers of 3x3 equal (± 2 px) rectangles to within a radius of 2.5 % of the minimum of the screen height or width; this is the measurement grid. The use of a pattern as in Figure 2 (AT02P) can be helpful in determining the correct measurement locations.
4. Measure and record the illuminance of the three nonatile tri-sequence patterns (Figure 3) at the nine locations of the measurement grid.

ANALYSIS: We use the matrix notation i, j , where $ij = 11$ is the upper left and $ij = 33$ is the lower right, to define the locations of the measurement grid—see Figure 4, i = row, j = column. The illuminance E_{ij} at any location i, j is given by the sum of the contributions from each of the three patterns at that location:

$$E_{ij} = E_{Rij} + E_{Gij} + E_{Bij}. \quad (1)$$

The flux Φ_{CSW} is given by the product of the projected area and the average illuminance:

$$\Phi_{\text{CSW}} = A E_{\text{ave}} = \frac{A}{9} \sum_{i,j=1}^3 E_{ij}. \quad (2)$$

REPORTING: Report the flux Φ_{CSW} to no more than three significant figures (unless more can be justified by an uncertainty analysis).

COMMENTS: None.

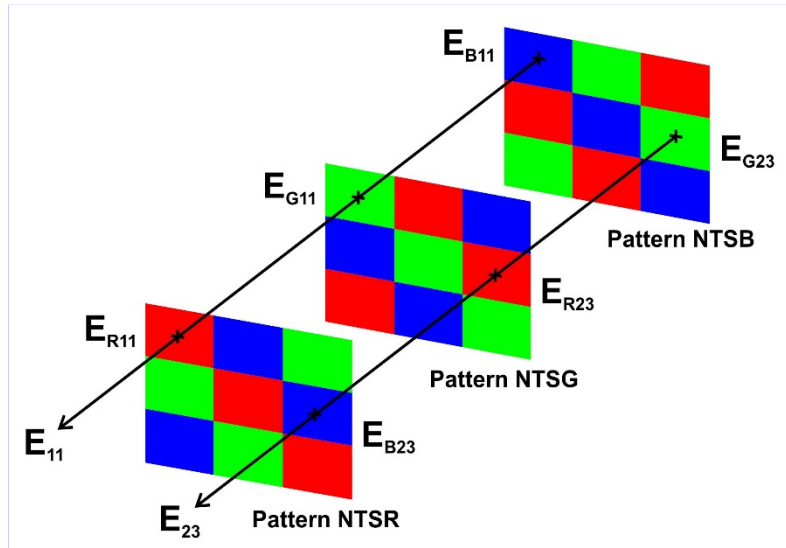


Fig. 4. Illuminance measurements of nonatile-trisequence patterns.

—SAMPLE DATA ONLY—						
Do not use any values shown to represent expected results of your measurements.						
Analysis Example:						
Pattern	Illuminance, E (lx)		Illuminance, E (lx)		Illuminance, E (lx)	
NTSR	$E_{R11} =$	260.1	$E_{B12} =$	67.0	$E_{G13} =$	1319.6
	$E_{G21} =$	1521.9	$E_{R22} =$	323.6	$E_{B23} =$	65.8
	$E_{B31} =$	70.8	$E_{G32} =$	1618.2	$E_{R33} =$	320.7
NTSG	$E_{G11} =$	1409.0	$E_{R12} =$	301.5	$E_{B13} =$	61.9
	$E_{B21} =$	67.6	$E_{G22} =$	1578.3	$E_{R23} =$	318.7
	$E_{R31} =$	287.7	$E_{B32} =$	70.4	$E_{G33} =$	1455.8
NTSB	$E_{B11} =$	63.0	$E_{G12} =$	1459.9	$E_{R13} =$	289.2
	$E_{R21} =$	278.5	$E_{B22} =$	70.7	$E_{G23} =$	1407.6
	$E_{G31} =$	1543.9	$E_{R32} =$	333.5	$E_{B33} =$	63.6
Illuminance at each location:	$E_{11} =$	1732.0	$E_{12} =$	1828.4	$E_{13} =$	1670.7
	$E_{21} =$	1868.0	$E_{22} =$	1972.6	$E_{23} =$	1792.2
	$E_{31} =$	1902.4	$E_{32} =$	2022.2	$E_{33} =$	1840.1
Average:	$E_{ave} =$	1847.6	Area, $A =$	1.116	m^2 (§ 15.2)	
Flux $\Phi_{CSW} =$	2061.9	lm				

<p align="center">—SAMPLE DATA ONLY—</p> <p align="center">Do not use any values shown to represent expected results of your measurements.</p>		
<p align="center">Reporting Example</p>		
Flux Φ_{CSW} =	2060	lm

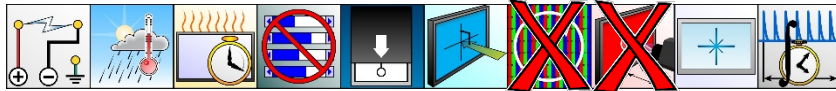


15.5 SEQUENTIAL CONTRAST RATIO

ALIAS: contrast, interframe contrast

DESCRIPTION: We measure the dynamic range of the display. This test is similar to that for a flat panel display, except that the luminance meter has been replaced by an illuminance meter. **Symbol:** C_{seq} .

APPLICATION: All front projection displays



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: If the projector lens has zoom and offset (or shift) controls, set the zoom control to “wide angle” and the offset (or shift) control to halfway between no offset and one end of its range. Setup an illuminance meter on the axis of the projector. Test patterns: full screen white and full screen black.

PROCEDURE:

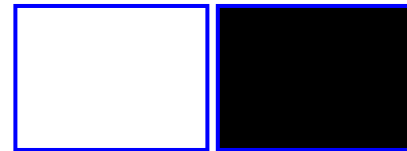
1. Measure the peak white illuminance, E_W .
2. Without changing any of the controls measure the black illuminance E_K .

ANALYSIS: Sequential contrast ratio is:

$$C_{seq} = E_W / E_K. \quad (1)$$

REPORTING: Report the Sequential Contrast, which has been calculated above.

COMMENTS: Be careful of stray light in making the black measurement.



—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Example:		
Center White Illuminance	Center Black Illuminance	Sequential Contrast Ratio
102.6	0.09	1140

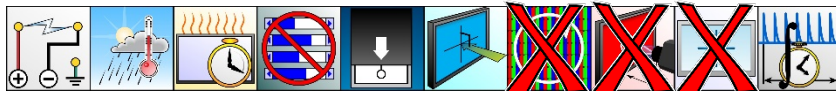
15.6 CHECKERBOARD CONTRAST RATIO

ALIAS: ANSI contrast, intraframe contrast

DESCRIPTION: We measure the contrast ratio of a checkerboard pattern. This test is similar to that for a flat panel display, except that the luminance meter has been replaced by an illuminance meter. **Symbol:** C_{CB} .

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Centralize the zoom and offset controls of the projection lens. Setup a black cloth, which covers the projection area, on the axis of the projector. Test pattern: $N \times M$ checkerboard with an equal number of alternating solid black and white rectangles. Mark the location on the cloth of the center of each of the test pattern rectangles.

PROCEDURE: Measure the illuminance at the center of each of the rectangles of the test pattern.

ANALYSIS: Calculate the checkerboard contrast as follows:

$$C_{CB} = \sum_{ij} C_W / \sum_{ij} C_K.$$

REPORTING: Report the checkerboard contrast calculated above and the test pattern used.

COMMENTS: The black illuminance can be very difficult to measure because of stray light and reflections from the room, even if a black screen is used. Accordingly, it is very important that a stray-light-elimination tube (SLET) or a projection mask be used when measuring the black illuminance.

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Example for 4 x 4 pattern:			
Screen Illuminance at 16 points			
0.066	16.12	0.078	15.99
15.42	0.068	21.21	0.075
0.069	22.95	0.081	22.89
19.65	0.075	25.63	0.072
Sum of White Illuminances			53.42
Sum of Black Illuminances			0.198
Checkerboard Contrast			270



15.7 WHITE POINT AND CORRELATED COLOR TEMPERATURE

ALIAS: color temperature

DESCRIPTION: We measure the color of the nominal white output and correlated color temperature (CCT) from the projector. This measurement is similar to that for a flat panel display. **Symbol:** x , y ; T_C

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Set up a white reflectance standard target on the axis of the projection display near the center of the projected image. Test pattern: full screen white.

PROCEDURE:

Measure the CIE (1931) chromaticity coordinates (x , y) of the light reflected from the white reference target.

ANALYSIS: If your color meter doesn't supply the CCT, then calculate the CCT from the chromaticity coordinates (x, y) by McCamy's approximation (C.S. McCamy, *Color Res Appl.* **17** (1992), pp 1542-144 (with erratum in *Color Res. Appl.* **18** (1993), p 150);

$$CCT = 437 n^3 + 3601 n^2 + 6861 n + 5514,$$

where

$$n = (x - 0.3320) / (0.1858 - y).$$

This approximation is close enough over the range 2,000 to 10,000K. Note that CCT only has meaning for y values close to the Planckian black body locus.

REPORTING: Report both the CIE (1931) chromaticity coordinates and the correlated color temperature.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
x	y	T_C
0.298	0.319	7503

15.8 RGB PRIMARY COLORS

ALIAS: red, green, blue

DESCRIPTION: We measure the color coordinates of the primaries of a front projection display. This test is similar to that for a flat panel display.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Disengage any color management settings in the projection display. Set up a white reflectance standard target on the axis of the projection display near the center of the projected image. Test pattern: full screen red, green, or blue.

PROCEDURE:

For each of the test pattern colors, measure the CIE (1931) chromaticity coordinates of the light reflected from the white reference target.

REPORTING: Report the chromaticity coordinates of each of the colors, red, green and blue.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Example:		
	x	y
Red	0.632	0.340
Green	0.295	0.610
Blue	0.141	0.057

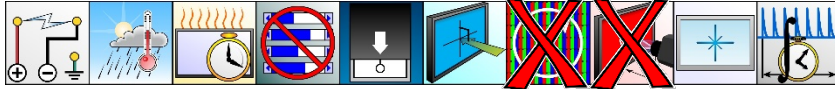


15.9 GRAY-SCALE ILLUMINANCE AND COLOR

DESCRIPTION: We measure the illuminance and color of a front projection display, as a function of the gray level (video signal level). These measurements may be used to calculate the “gamma” of the display. These measurements are also similar to those for a flat panel display (see § 7 Gray-Scale and Color-Scale Metrics). **Symbol:** x , y , E .

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: For the illuminance measurements, set up an illuminance meter on the axis of the front projection display. For the color measurements, set up a white reference target on the axis of the projection display. Test pattern: full screen gray, of various digital video levels.

PROCEDURE:

1. Measure the illuminance for each gray shade.
2. Measure the CIE (1931) chromaticity coordinates of the light reflected from the white reference target for each gray shade.

REPORTING: Report the table shown on the right. A graphical representation may also be used.

COMMENTS: Low level illuminance can be difficult to measure because of stray light. Accordingly, it is suggested that a SLET device be used when measuring the low level illuminance. We show eight levels here in the example. However, any number of levels may be measured depending upon the needs. See § 7 Gray-Scale and Color-Scale Metrics for more information and other metrics that can employ these data.

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Example:			
gray level	Illuminance, E (lx)	x	y
0	0.09	0.313	0.329
36	1.76	0.310	0.330
72	6.48	0.311	0.328
109	15.29	0.314	0.330
145	28.32	0.312	0.331
182	46.78	0.311	0.333
218	70.11	0.310	0.330
255	99.10	0.312	0.328





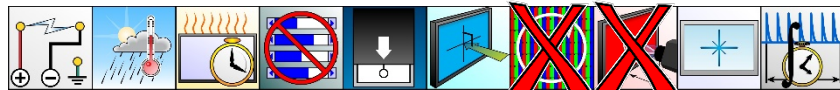
15.10 RESOLUTION AND CONTRAST MODULATION

ALIAS: effective resolution, pixel size degradation

DESCRIPTION: We measure the effective resolution and the pixel-size degradation of the projector based upon how well the projector resolves black and white single-pixel and double-pixel lines from a contrast measurement. **Units:** px for pixel-size degradation, none for resolution, **Symbol:** ΔP for pixel-size degradation, and $(N \times M)$ for effective resolution.

APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Four test patterns: vertical and horizontal lines with one pixel on and one pixel off and also with two pixels on and two pixels off. Measuring instrument: imaging photometer. The array detector should have a sufficient resolution to cover a number of projected pixel lines (10 or more is suggested) and be set up so that each line in the test pattern covers at least 10 pixels, preferably more.

PROCEDURE:

1. Capture images of the test pattern of 1×1 lines for both vertical and horizontal lines.
2. Capture images of the test pattern of 2×2 lines for both vertical and horizontal lines.

ANALYSIS: For each captured image, measure the average maximum luminance (L_W) and the average minimum luminance (L_K) for each of the four test patterns, where we average over a number of projected pixels to obtain a smooth profile. The contrast (Michelson) modulation is then given by:

$$C_m = (L_W - L_K) / (L_W + L_K).$$

Resolution for text or graphics is defined as that pixel spacing for which C_m has fallen to 50%. If C_{m2} for 2×2 is greater than 50% and C_{m1} for 1×1 is less than 50%, then the effective resolution may be calculated by linear interpolation between the one- and two-pixel data to find the value where the C_m equals 50%: The effective size of the pixel is then greater than one pixel:

$$\Delta P = (C_{m2} - 2C_{m1} + 0.5) / (C_{m2} - C_{m1}) > 1.$$

The effective resolution $(N' \times M')$ of the projector is degraded from its native resolution $(N \times M)$ by

$$(N' \times M') = ([N / \Delta P_H] \times [M / \Delta P_V]),$$

where ΔP_H and ΔP_V are the effective pixel sizes in the horizontal and vertical directions from an analysis of the vertical and horizontal lines, respectively (the fuzziness of vertical lines indicates a horizontal degradation in resolution, and the fuzziness of horizontal lines indicates a vertical degradation of resolution). If $C_{m1} > 50\%$ report an effective pixel size of $\Delta P = 1$ pixel. If $C_{m2} < 50\%$, see Comments.

REPORTING: Report the effective pixel resolution of the display.

COMMENTS: (1) **Michelson Contrast:** The contrast defined here, called “contrast modulation” from legacy terminology, is also known as the Michelson contrast. (2) **Poorer Resolution:** With modern projectors, it is unlikely that we will need to go beyond one-pixel or two-pixel lines. If $C_{m2} < 50\%$, repeat the measurements for a 3×3 pattern and interpolate between the 2×2 and 3×3 contrast modulations in a similar manner as above. See § 8.9 Resolution from Contrast Modulation for more information. (3) **Extension:** Whereas this measurement is made at the center screen, it can readily be extended to any place on the screen.

—SAMPLE DATA ONLY—						
Do not use any values shown to represent expected results of your measurements.						
Analysis & Reporting Example:						
Pitch	Vertical Lines			Horizontal Lines		
	L_W	L_K	C_m	L_W	L_K	C_m
1 x 1	30	15	0.33	31	16	0.32
2 x 2	39	6	0.73	38	5	0.77
Degradation	$\Delta P_H =$	1.42		$\Delta P_V =$	1.40	
Native Resolution	1024 x 768		Effective Resolution		904 x 513	



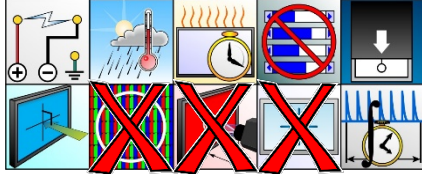
15.11 SAMPLED UNIFORMITY OF FULL-WHITE LUMINANCE

ALIAS: nonuniformity, uniformity

DESCRIPTION: We measure the non-uniformity of the illumination from front projection display. Note that we speak of this as a uniformity measurement, but we really measure the nonuniformity.

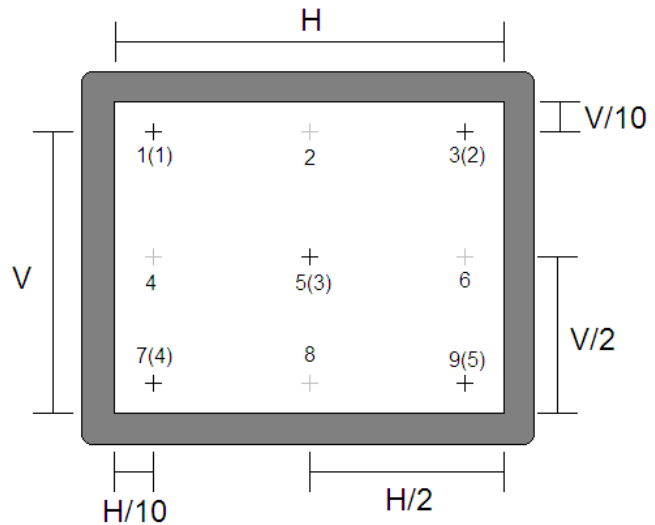
APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument:

Method 1: illuminance meter. Method 2: Imaging photometer or colorimeter. For Method 1 using the illuminance meter, the measurement points are arranged in an X or in a 3 × 3 array with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (See Figure). Test pattern: Full screen white.



PROCEDURE:

Method 1: Measure the illuminance of the projector at 5 or 9 points, on a rectangular grid as shown in the figure above.

Move the illuminance meter to the different locations. Record the maximum E_{\max} and the minimum E_{\min} values of the illuminance.

Method 2: Capture an image of the screen using the imaging photometer or colorimeter that has been properly configured for this kind of measurement and calibrated with the screen being used. Measure the luminance at the desired locations.

Record the maximum L_{\max} and the minimum L_{\min} values of the luminance.

ANALYSIS:

- Method 1:** Nonuniformity = 100 % [$(E_{\max} - E_{\min}) / E_{\max}$].
- Method 2:** Analyze data according to that described in § 9.7 Area Statistical Analysis of Uniformity.

REPORTING: Report the nonuniformity to 2 significant figures, the measurement method used, the number of points measured (5 or 9) and whether they were measured normal to the screen or from a single vantage point as in Method 2. For Method 2, report results in accordance with § 9.7 Area Statistical Analysis of Uniformity.

COMMENTS: (1) **Uniformity:** The above calculates nonuniformity.

Uniformity = 100 % (E_{\min} / E_{\max}) . (2) **Spectral Composition of**

Source: The particular spectrum of the light source may not affect the results significantly, but for the highest precision

spectrally resolved measurements should be used. (3) **Coverage:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around, and the results averaged.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
Illuminance at 9 points (lx)		
81.1	80.2	79.8
82.3	80.7	78.1
84.0	81.4	80.3
E_{\max}	E_{\min}	Non-uniformity
84.0	78.1	7.0 %



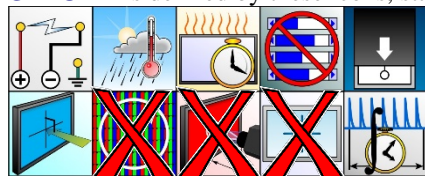
15.12 SAMPLED UNIFORMITY OF DARK-GRAY LUMINANCE

ALIAS: dark gray nonuniformity, dark gray uniformity

DESCRIPTION: We measure the non-uniformity of the dark image of a front projection display

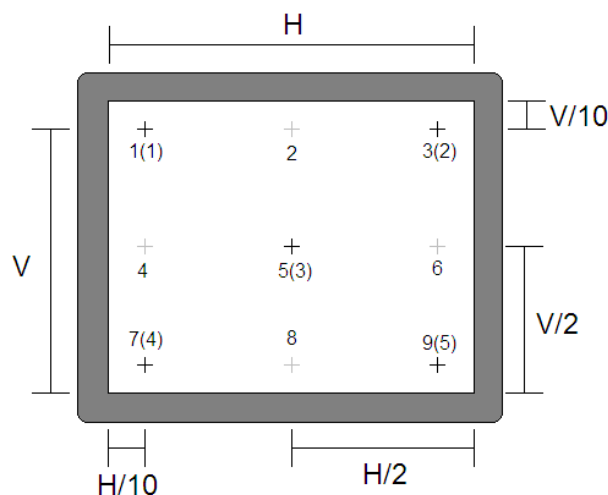
APPLICATION: All front projection displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument:

Method 1: Illuminance meter. Method 2: Imaging photometer or colorimeter. For Method 1 using the illuminance meter, the measurement points are arranged in an X or in a 3×3 array with the edge points located $1/10$ of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (See Figure). Test Pattern: Full screen dark gray with a level between 5 and 15% of the white level.



PROCEDURE:

Method 1: Measure the illuminance of the projector at 5 or 9 points, on a rectangular grid as shown in the figure above.

Move the illuminance meter to the different locations. Record the maximum E_{\max} and the minimum E_{\min} values of the illuminance.

Method 2: Capture an image of the screen using the imaging photometer or colorimeter that has been properly configured for this kind of measurement and calibrated with the screen being used. Measure the luminance at the desired locations.

Record the maximum L_{\max} and the minimum L_{\min} values of the luminance.

ANALYSIS:

- Method 1:** Nonuniformity = $100 \% [(E_{\max} - E_{\min}) / E_{\max}]$.
- Method 2:** Analyze data according to that described in § 9.7 Area Statistical Analysis of Uniformity.

REPORTING: Report the non-uniformity to 2 significant digits, the dark gray level, the measurement method used, the number of points measured (5 or 9) and whether they were measured normal to the screen or from a single vantage point. For procedure 2, report results in accordance with § 6.4.1 (Area Statistical Analysis of Uniformity).

COMMENTS: (1) **Uniformity:** The above calculates nonuniformity.

Uniformity = $100 \% (E_{\min} / E_{\max})$. (2) **Spectral Composition of**

Source: The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. (3) **Coverage:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around, and the results averaged.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
Illuminance at 9 points		
0.21	0.20	0.19
0.22	0.20	0.18
0.24	0.21	0.20
Max.	Min.	Non-uniformity
0.24	0.18	25 %



16. FRONT-PROJECTOR-SCREEN MEASUREMENTS

Any front projector needs to be used with a screen, even if it is only a wall, to show an image. Accordingly, the screen inherently affects the performance of any projection system. The screen needs to be a diffuse reflector. A mirror does not make an effective screen. Effective screens can be matte white, matte gray or matte silver. This section describes how to make those measurements that are needed to characterize the performance of a front projector screen. Measurements do not need to be made on the whole screen but can be made on a sample of the screen material. Adjustments may only be made to the projector prior to measurements being started. No adjustments may be made during the data acquisition itself.

A front projector screen is not a light emitter, but only reflects that light that is shone upon it. Therefore, all measurements are made relative to that illumination. For example, a screen has no inherent color, but can shift the color of the light shone upon it. Brightness is compared with that from an ideal Lambertian reflector, and the ratio is called the *gain*.

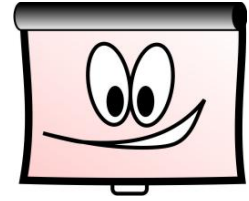
The important parameters for characterizing a front projection screen are:

1. Color shift
2. Color shift uniformity
3. Contrast enhancement
4. Gain
5. Gain Directivity
6. Gain Uniformity

Contrast enhancing screens are those gray screens that are designed to enhance the contrast of the projected image in a room with light colored walls. These are typically used in consumer home theaters, but not generally in professional studios or theaters, which have dark colored walls.

Other factors, such as the flatness of the screen, the surface finish and how it affects resolution and the ability of the screen to preserve the polarization of light, from a polarized projector, are not addressed in this version of the standards.

Gain measurements of the screen are made by using a reference target, with a quasi-Lambertian directivity. However, although a typical Lambertian reference target has a total integrated reflectance, or reflectivity, of around 99%, the gain at normal incidence and the reflectance is not usually defined. This gain at normal incidence is typically a little greater than 1.0. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed using both a luminance and an illuminance meter, as described below.



Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



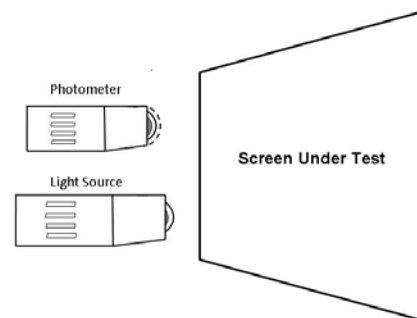
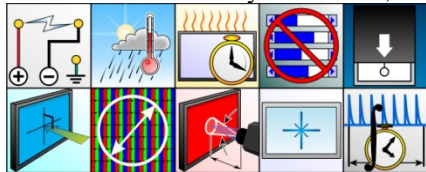
16.1 SCREEN COLOR SHIFT

ALIAS: Screen color

DESCRIPTION: Measure shift in color produced by a screen when reflecting the incident light. However, this test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** none. **Symbols:** $\Delta u'v'$, u'_{ref} , v'_{ref} , u'_{screen} , v'_{screen} .

APPLICATION: Front-Projection Screens

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument – colorimeter or spectroradiometer. Light source - a stable broadband source, such as that with which the screen is intended to be used. Color reference target which is spectrally neutral and near Lambertian. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5 degrees.

PROCEDURE: The screen color shift shall be measured relative to the color reference target.

Measure the color (u'_{ref} , v'_{ref}) and correlated color temperature (T_{target}) of the reference target at the intersection of the normal with the screen.

Measure the color (u'_{screen} , v'_{screen}) and correlated color temperature (T_{screen}) of the screen at the same location as the target had been located.

ANALYSIS:

1. Color Shift = $\Delta u'v' = \sqrt{(u'_{\text{ref}} - u'_{\text{screen}})^2 + (v'_{\text{ref}} - v'_{\text{screen}})^2}$
2. CCT Shift = $T_{\text{screen}} - T_{\text{target}}$

REPORTING: Report the amplitude of the color shift of the screen, to three decimal places, and, optionally, the shift in correlated color temperature CCT, to three significant digits.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:

u'_{ref}	v'_{ref}	T_{target}	u'_{screen}	v'_{screen}	T_{screen}	$\Delta u'v'$	CCT Shift
0.197	0.469	6533	0.195	0.465	6671	0.004	138

COMMENTS: Note that screens should not inherently have any color, but they can change the color of a projected image. If the screen is intended for use with a light source which is not broadband, such as a laser light source, then the color shift should be measured with the intended light source instead of a broadband light source.



16.2 SCREEN COLOR UNIFORMITY

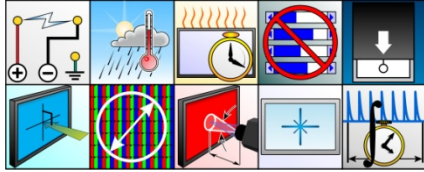
ALIAS: Color nonuniformity, color variation

DESCRIPTION: Measure the uniformity of the color of a screen when reflecting the incident light. This test need not be conducted on the full-size screen and may be conducted on a small sample of screen material.

Units: non-dimensional. **Symbols:** u'_{mean} , v'_{mean} , $\Delta u'v'$.

APPLICATION: Front-projection screens.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Minimum screen sample size is 1 m².

Measuring instrument: colorimeter or spectroradiometer or an imaging colorimeter. Light source: a stable broadband source, such as a projector with which the screen is intended to be used. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5° or set up an imaging colorimeter normal to the screen.

The measurement points are arranged in a 3 × 3 array, with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (see the figure). All points should be measured either with the instrument normal to the screen or from a single vantage point.

PROCEDURE:

1. Either: Using a colorimeter or spectroradiometer, measure the color of the screen, (u' , v'). Repeat the measurements of the color at nine points on the rectangular grid in the figure above. Either move the light source and meter together over the screen or keep the light source and meter fixed and move the screen to the various locations. Record the color, (u' , v') for each point.
2. Alternatively, capture an image of the screen using an imaging colorimeter. Compute the color of the screen, (u' , v'), for each point of the screen image.

ANALYSIS:

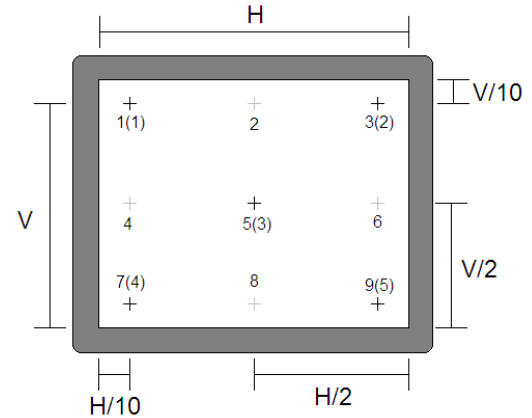
1. Calculate the mean color of the screen u'_{mean} , v'_{mean} ,
2. Calculate the color variation of each point from the mean,

$$\Delta u'v' = \sqrt{(u'_{\text{ref}} - u'_{\text{screen}})^2 + (v'_{\text{ref}} - v'_{\text{screen}})^2}$$

3. Identify the maximum color variation, $\Delta u'v'_{\text{max}}$

REPORTING: Report the maximum color variation of the screen, the measurement method used, the number of points measured and whether they were measured normal to the screen or from a single vantage point.

COMMENTS: If the screen is intended for use with a light source which is not broadband, such as a Laser light source, then the color should be measured with the intended light source instead of a broadband light source.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:

	u'	v'	$\Delta u'v'$
Upper Left	0.197	0.469	0.0014
Center Left	0.197	0.469	0.0014
Lower Left	0.200	0.468	0.0020
Upper Center	0.198	0.469	0.0004
Center	0.198	0.470	0.0009
Lower Center	0.200	0.468	0.0020
Upper Right	0.198	0.469	0.0004
Center Right	0.198	0.471	0.0018
Lower Right	0.200	0.470	0.0018
Mean	0.1984	0.4692	
Maximum $\Delta u'v'_{\text{max}}$ =			0.0020



16.3 SCREEN CONTRAST ENHANCEMENT

ALIAS: Gray screen, non-darkroom contrast of a screen, effective contrast

DESCRIPTION: Measure the effectiveness of the gain and directivity of a projection screen material at enhancing the image contrast in a room with a light décor. The screen material can do this by reducing the light from the image which is reflected back off the walls and on to the screen. This test need not be conducted on the full-size screen but on a small sample of screen material. This test is not intended for the measurement of a short-throw projector with a dedicated screen, but rather for a stand-alone screen material for use with longer-throw projectors. **Units:** none. **Symbols:** \mathcal{E}_C .

APPLICATION: Front-projection screens for the home.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Screen sample size: approximately 1 m (3.3 ft) wide by 0.56 m (1.8 ft) high. Measuring instrument: 2° or less spot luminance meter. Light source: a projector with a stable broadband light source and a near D65 (x, y) = (0.313, 0.329) color. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5 degrees. Test pattern: 4 × 4 checkerboard. Test chamber: Integrating sphere or a rectangular box, 2.1 m (7 ft) long by 1.5 m (5 ft) wide and 0.9 m (3 ft) high. Interior finish: matte white paint as described in comments.

PROCEDURE: Measure the luminance L_{Wi} , L_{Ki} , $i = 1, 2, \dots, 8$ of each of the eight white and eight black boxes, respectively, of the 4 × 4 checkerboard test pattern under two conditions:

Condition 1: With the projector and screen material sample in a large darkroom. This measures the contrast ratio of the projector and screen with minimal wall reflections.

Condition 2: With the screen material sample in the “white test chamber”. This measures the contrast ratio of the projector and screen with wall reflections.

ANALYSIS: Calculate the checkerboard contrast for each of the two cases above. The contrast is defined as the sum of the white luminances divided by the sum of the black luminances:

$$C = \left(\sum_{i=1}^8 L_{Wi} \right) \left(\sum_{i=1}^8 L_{Ki} \right)^{-1}$$

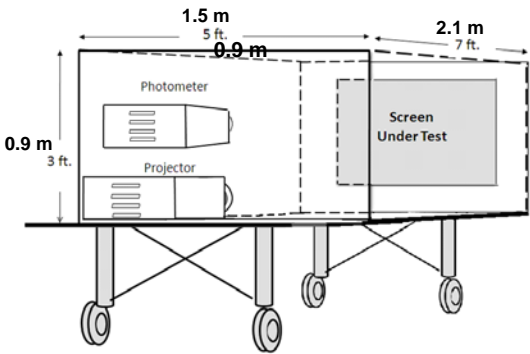
The checkerboard contrast measured in the large darkroom is C_D , and the checkerboard contrast measured in the test chamber is C_T . The effective contrast \mathcal{E}_C is determined by

$$\mathcal{E}_C = C_D C_T / (C_T - C_D).$$

REPORTING: Report the effective contrast \mathcal{E}_C of the screen material and report the size of the test chamber used to make the measurement.

COMMENTS: In a typical movie theater or screening room, the walls and ceiling are dark and minimal amount of light from the screen is reflected back on to the screen to degrade the picture contrast. Here white screens are generally used. However, in a home theater, the walls and ceiling have a light color, even white. Much light reflecting from the screen is scattered back onto the screen and reduces the contrast of the picture. It has been found that screens with a gray color and significant directivity can significantly mitigate this contrast reduction.

This procedure measures the effect of the chamber on the contrast of an image projected on to a sample of the screen material. This measurement will be critically dependent upon the geometry and surface finish of the test chamber. This



—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Analysis example:			
Screen Luminances at 16 points, (cd/m ²)			
0.66	16.12	0.78	15.99
15.42	0.68	21.21	0.75
0.69	22.95	0.81	22.89
19.65	0.75	25.63	0.72
Sum of White Luminances			53.42
Sum of Black Luminances			1.98
Checkerboard Contrast			27.0

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting example		
Darkroom Contrast	Test Room Contrast	Effective Contrast, \mathcal{E}_C
104	26.8	36
Test Room Size:		
Length	Width	Height
2.1 m	1.5 m	0.9 m



chamber needs to be standardized and reproducible by anyone who wishes to replicate it. Such a standard chamber might be a sampling sphere with a white Lambertian interior surface. However, such a chamber is not typical of the final application. It will weigh the effects of screen directivity and gain differently from a real home theater room. A test chamber which is a geometric model of a real home theater will weigh the two parameters more realistically. A one third scale model is considered appropriate. This will give dimensions of 2.1 m (7 ft) long by 1.5 m (5 ft) wide and 0.9 m (3 ft) high. The screen sample shall be 1 m (3.3 ft) wide by 0.56 m (1.8 ft) high.

The nature of the interior finish of the test chamber is also very important. The walls, ceiling and floor shall all be the same finish, for the sake of simplicity. This finish shall be a matte white paint with a reflectance $\rho \geq 0.90$. A topcoat shall be applied to control the matte nature of the finish.

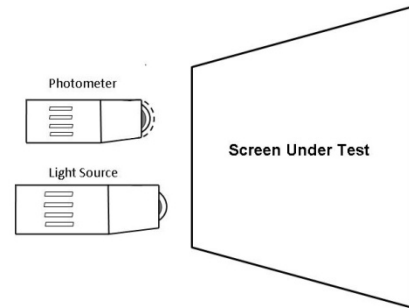
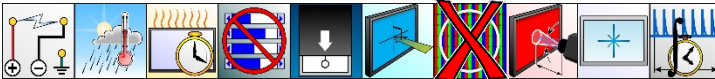
16.4 SCREEN GAIN

ALIAS: Reflectance, reflectance factor, gain

DESCRIPTION: Measure the gain of a front projection screen, normal to the screen. This gain is the ratio of the luminance of an image on the screen relative to the luminance which would be seen from a perfectly reflecting diffuser. This test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** none. **Symbols:** G .

APPLICATION: Front-Projection Screens. The primary intention is for this to be a laboratory measurement where the measuring distance is a few meters. However, it may also be used in theaters where the light source is a long distance from the screen.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Measuring instrument – Luminance meter and either an illuminance meter or a near Lambertian reference target with a known gain G_{std} (see comments) for the source-detector geometry employed. Light source: a stable broadband source, such as an Illuminant-A source with a diffuser and a blue filter to create a near D65 (x, y) = (0.313, 0.329) color. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5° . In the laboratory the light source and meter are approximately the same distance from the screen, but in a theater, the meter may be closer to the screen than the light source.

PROCEDURES:

1. Either measure the incident light flux (E), at the intersection of the normal with the screen using an illuminance meter, or measure the luminance (L_0) of the light reflected at the intersection of the normal to the screen at the same location using a luminance meter.
2. Or: Place the reference target at the same location as the screen. Make sure that the reference target fills the field of view of the luminance meter. Measure the luminance of the reference target (L_{std}). Replace the reference target with the screen and measure the luminance of the screen (L_0).

ANALYSIS: Depending upon the procedure used, the gain is calculated:

1. Gain: $G = \pi L_0 / E$
2. Gain: $G = G_{std} L_0 / L_{std}$

REPORTING: Report the Gain of the screen and which of the two measurement methods was used.

COMMENTS: (1) Reference Target: A typical so-called Lambertian reference target has a reflectance of approximately 99% for a uniform diffuse hemispherical illumination. However, the reflectance factor is not going to be 0.99 for just any illumination condition because such targets are not truly Lambertian. Their gain is typically a little greater than 1.0 with the source and detector near its normal. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed with a luminance and an illuminance meter as described above.

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Analysis example:			
Illuminance E	Screen Luminance L_0		Screen Gain $\pi L_0 / E$
130.2	40.4		0.975
Target Luminance L_{std}	Screen Luminance L_0	Target Gain G	Screen Gain $G_{std} L_0 / L_{std}$
45.5	40.4	1.1	0.975



(2) **Spectrally Resolved Measurements:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. (3) **Coverage of Illuminance Meter:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around, and the results averaged. (4) **Sensitivity:** Be aware that Procedure 1 is sensitive to the accuracy of both the luminance meter and the illuminance meter, whereas Procedure 2 is only sensitive to the accuracy of the calibration of the reference target.

16.5 SCREEN GAIN DIRECTIVITY

ALIAS: Reflectance Directivity, Reflectance Factor Directivity, Angular Gain Measurement, Gain Angular Distribution.

DESCRIPTION: Measure the directivity of the Gain of the front-projector screens. However, this test need not be conducted on the full-size screen and may be conducted on a small sample of screen material.

Units: none. **Symbols:** Θ .

APPLICATION: Front-Projection Screens. The primary intention is for this to be a laboratory measurement where the measuring distance is a few meters. However, it could also be used in theaters where the light source is a long distance from the screen. Most screens are isotropic and in this case, measurements need only be made about one axis θ . However, some recent screens can be anisotropic, and in this case measurements need to be made about both axes θ and ϕ .

SETUP: As defined by these icons, standard setup details apply



(§ 3.2).

OTHER SETUP CONDITIONS: Measuring instrument – Luminance meter and either an illuminance meter or a near Lambertian reference target with a known gain, G_{std} (see comments). Light source - a stable broadband source, such as an Illuminant A source with a diffuser and a blue filter to create a near D65 (x, y) = (0.313, 0.329) color. The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5°. In the laboratory the light source and meter are approximately the same distance from the screen, but in a theater, the meter may be closer to the screen than the light source.

PROCEDURE:

1. **BRDF measurement:** This is the most comprehensive measurement and yields all of the properties that might be desired
2. **Alternative 1:** (for evaluating the audience size) Measure the gain G normal to the screen using one of the methods described in § 16.4. Measure the luminance L_0 of the screen normal to its surface and the Luminance L_θ at the desired angles. Keep the light source normal to the screen and move the meter
3. **Alternative 2:** (for evaluating the screen appearance to a single viewer) Keep both the light source and meter fixed and rotate the screen about a vertical axis.
4. **Alternative 3:** (for evaluating ambient light rejection) Keep both the meter and screen fixed and move the light source.

ANALYSIS:

1. **Gain at angle θ ,**

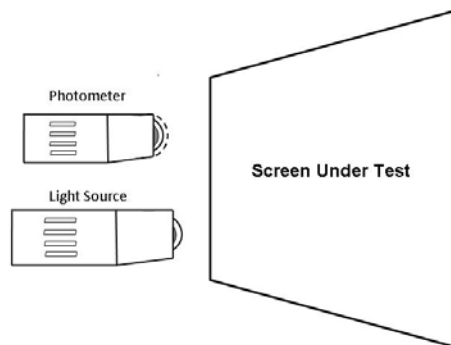
$$G = \pi L_0 / E,$$

$$\text{or } G = G_{std} L_0 / L_{std}.$$

2. **Viewing Angle:**

Determine the angles θ_1 and θ_2 where the gain has fallen to 50% of the gain measured normal to the screen. The viewing angle Θ is given by

$\Theta = (\theta_1 - \theta_2)/2$. If the Gain never falls below 50% of the value measured at normal, report a value of 90°.



—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Analysis example:				
Horizontal Angle to Normal	Illuminance E (lx)	Screen Luminance, L_0 (cd/m ²)		Screen Gain $\pi L_0 / E$
-15°	130.2	40.4		0.975
Vertical Angle To Normal	Target Luminance, L_{std} (cd/m ²)	Screen Luminance, L_0 (cd/m ²)	Target Gain, G_{std}	Screen Gain $G_{std} L_0 / L_{std}$
+15°	45.5	40.4	1.1	0.975



REPORTING: Report a table of the Gain for the screen versus angle to the normal and the measurement method which was used. Report the viewing angle for the screen.

COMMENTS: (1) **Reference Target:** A typical so-called Lambertian reference target has a reflectance of approximately 99% for a uniform diffuse hemispherical illumination. However, the reflectance factor is not going to be 0.99 for just any illumination condition because such targets are not truly Lambertian. Their gain is typically a little greater than 1.0 with the source and detector near its normal. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed with a luminance and an illuminance meter as described above. (2) **Spectrally Resolved Measurements:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. (3) **Coverage of Illuminance Meter:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around, and the results averaged. (4) **Sensitivity:** Be aware that Procedure 1 is sensitive to the accuracy of both the luminance meter and the illuminance meter, whereas Procedure 2 is only sensitive to the accuracy of the calibration of the reference target.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting example		
Orientation	Angle to Normal	Screen Gain
Horizontal	- 30°	0.719
	- 22°	0.733
	- 15°	0.740
	0°	0.797
	+ 15°	0.725
	+ 22°	0.711
	+30°	0.705
Vertical	- 15 °	0.740
	0°	0.797
	+ 15°	0.725

16.6 SCREEN GAIN UNIFORMITY

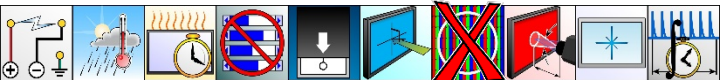
ALIAS: gain nonuniformity

DESCRIPTION: Measure the uniformity (and nonuniformity) of the gain of a front projection screen. However, this test need not be conducted on the full-size screen and may be conducted on a small sample of screen material. **Units:** non-dimensional

Symbols: U_G , N_G .

APPLICATION: Front-projection screens. The primary intention is for this to be a laboratory measurement where the measuring distance is a few meters. However, it could also be used in theaters where the light source is a long distance from the screen.

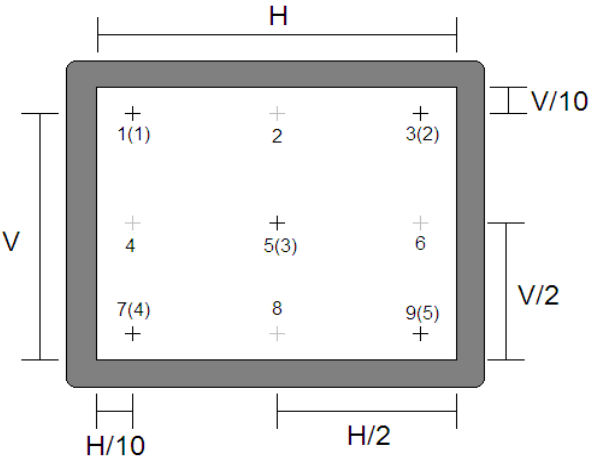
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: The meter and light source shall be located symmetrically about the normal to the screen and include a total angle of less than 5 degrees. In the laboratory the light source and meter are approximately the same distance from the screen, but in a theater, the meter may be closer to the screen than the light source. Reflectance target which is spectrally neutral and near-Lambertian. Light source: a stable broadband source, such as an Illuminant A source with a diffuser and a blue filter to create a near D65 (x, y) = (0.313, 0.329) color. The measurement points are arranged in a 3x3 array, with the edge points located 1/10 of the vertical or horizontal screen size from the edges of the screen, and the middle points centered between the edges (see figure). All points should be measured either with the instrument normal to the screen or from a single vantage point. **Method 1:** Measuring instrument: luminance meter and either an illuminance meter or a near Lambertian reference target with a known gain, G_{std} (see comments). **Method 2:** An imaging photometer or colorimeter is located normal to the screen. Measuring instrument: imaging photometer or colorimeter.

PROCEDURE: Perform either of the following two measurement procedures:

1. Measure the gain of the screen using one of the methods described in § 16.4. Repeat these measurements, at 5 or 9 points, on a rectangular grid as shown in the figure above. Either move the light source and meter together over the





screen or keep the light source and meter fixed and move the screen to the different locations. Record the maximum G_{\max} and the minimum G_{\min} values for the gain.

- Or: Capture an image of the screen using the imaging photometer or colorimeter. Measure the illuminance of the screen or the luminance of a reference target at desired locations on the screen. Compute the gain of the screen for each of these locations. Record the maximum G_{\max} and the minimum G_{\min} values for the gain.

ANALYSIS:

- Gain Uniformity: $U_G = 100 \% \times G_{\min} / G_{\max}$.
Gain Nonuniformity: $N_G = [(G_{\max} - G_{\min}) / G_{\max}] \times 100 \%$.
- For procedure 2, analyze data according to that described in section 8.2.2 Area Statistical Analysis of Uniformity.

REPORTING: Report the nonuniformity of the gain of the screen, to two significant digits, the measurement method used, the number of points measured (5 or 9) and whether they were measured normal to the screen of from a single vantage point. For procedure 2, report results in accordance with § 8.2.2 Area Statistical Analysis of Uniformity.

COMMENTS: (1) **Reference Target:** A typical so-called Lambertian reference target has a reflectance of approximately 99% for a uniform diffuse hemispherical illumination. However, the reflectance factor is not going to be 0.99 for just any illumination condition because such targets are not truly Lambertian. Their gain is typically a little greater than 1.0 with the source and detector near its normal. It is important for this measurement that the gain of the reference target be calibrated for the same source-sample detector geometry as being employed in the chosen measurement procedure. This calibration can be performed with a luminance and an illuminance meter as described above. (2) **Spectrally Resolved Measurements:** The particular spectrum of the light source may not affect the results significantly, but for the highest precision spectrally resolved measurements should be used. (3) **Coverage of Illuminance Meter:** If an illuminance meter covers less than 500 pixels, then the meter should be moved around, and the results averaged. (4) **Sensitivity:** Be aware that Procedure 1 is sensitive to the accuracy of both the luminance meter and the illuminance meter, whereas Procedure 2 is only sensitive to the accuracy of the calibration of the reference target.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Analysis example:		
Screen Luminance at nine points (cd/m ²)		
81.1	80.2	79.8
82.3	80.7	78.1
84.0	81.4	80.3
G_{\max}	G_{\min}	Nonuniformity
84.0	78.1	7.0 %



17. 3D & STEREOSCOPIC DISPLAYS

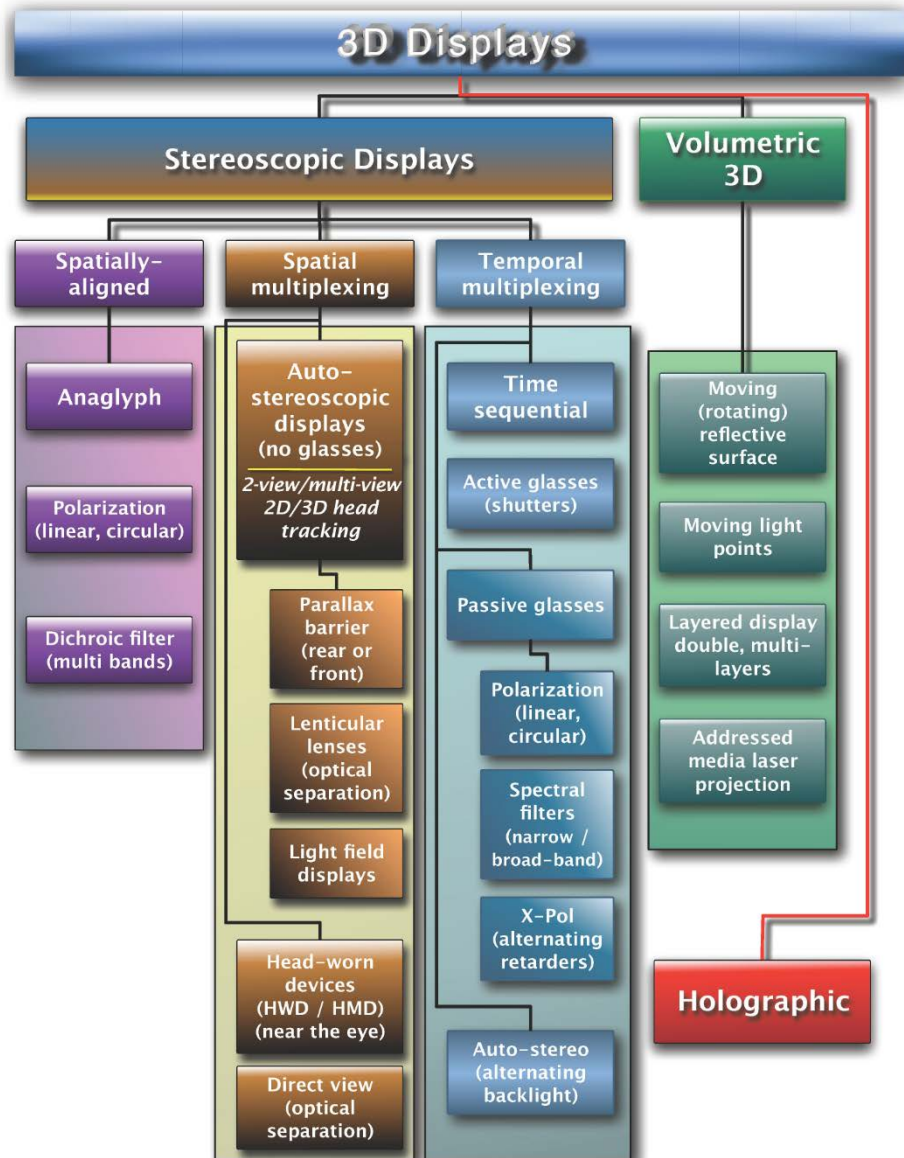
This chapter deals with the measurements of 3D displays, with an emphasis on stereoscopic (stereo) displays. In revision II we expanded the light-field holographic and volumetric displays. It is primarily oriented for direct view displays, but most techniques can be applied to projection 3D displays imaged on a screen. Similarly, some techniques will be applicable to near-the-eye 3D displays. It discusses methods and procedures for the characterization of display performance. There are several technologies used to create 3D displays and the user may need to choose among the different methods for each type of technology under consideration. Accordingly, the purpose of this chapter is to establish a generic set of methods, and let the user decide which ones are most applicable for their technology. The following diagram illustrates the complexity of the 3D display family tree; it is not intended to be studied, nor do we attempt to measure all these display types.

Currently we deal with only four types of stereo displays in this chapter—see Table 1. Because different types of 3D displays have their own unique set of problems, we have placed all the pertinent material in this chapter in the introduction as we have done similarly for the projection displays. This is a departure from much of the rest of this document where a separate metrology appendix and tutorial appendix are provided. (Note that much of the material in those appendices applies to 3D displays).

In conjunction with these types of displays, another important feature of this chapter is establishing a precise terminology for dealing with 3D displays. To that end, we follow these introductory remarks with some definitions that are used in dealing with 3D displays. Some of these ideas are rather complicated and difficult to understand; hence, the first section of this chapter is devoted to establishing the mathematical framework to further define some of these terms.

There are a number of examples of patterns that may be used to visually test, measure, and inspect stereo displays that appear at the back of this chapter, § 17.6.1 Stereoscopic Display Patterns.

In the discussions and measurements in this chapter we use the following notation: L_{LQ} , L_{RQ} . Here, L means the left-eye view, R means the right-eye view, the left- and right-most Q is the selected color for the left- and right-eye channel, respectively, where $Q = R, G, B, C, M, Y, W, K, S$ (gray shade), or any required RGB color. For example, L_{LWK} is the luminance of the left-eye view where the left-eye channel is white, and the right-eye channel is black.



**Table 1.** 3D stereo displays with measurement support in this chapter

3D display measurement category	Display types	Observational or measurement conditions
17.2 Stereoscopic displays that require glasses (passive and active)	Anaglyph	Glasses with broadband colored filters
	Dichroic color filter	Dichroic filters (narrow bands) glasses
	Patterned retarder	Circular polarizing glasses
	Linear polarizing	Linear polarizing glasses
	Projection	Circular or linear polarizing glasses
	Time sequential (temporally multiplexed)	Shutter glasses
	Time sequential (temporally multiplexed)	Circular or linear polarizing glasses (passive)
17.3 Autostereoscopic displays with two views	Parallax barrier	Single head position for best 3D view
	Lenticular lenses	Single head position for best 3D view
	2D/3D switching (parallax barrier, or lenticular lenses)	Single head position for best 3D view
	Head tracking (parallax barrier)	Tracking option should be eliminated during tests.
17.4 Autostereoscopic displays with multiple views	Parallax barrier	Multiple head positions for 3D view
	Lenticular lenses	Multiple head positions for 3D view
	2D/3D switching (parallax barrier, or lenticular lenses)	Multiple head positions for 3D view
17.5 Autostereoscopic displays with viewing field (light-field)	Light-field displays	Continuous region in space for 3D view

TYPES OF 3D DISPLAYS:

3D display – a display that provides a different view for each eye that simulates our view of the three-dimensional world. It includes stereoscopic displays, volumetric displays, and holographic displays.

stereoscopic display, stereo display – a type of 3D display that creates the perception of three-dimensional objects and scenes by introducing lateral shifts in corresponding monocular images presented on a two-dimensional (flat) screen.

autostereoscopic display – a stereo display that does not require the wearing of special glasses or eyewear to see the 3D effects.

holographic display – a display that permits an observer to perceive 3D objects because each of the observer's eyes sees a given scene from a different perspective (which also provides motion parallax in addition to binocular parallax when the observer makes lateral head movements); holographic displays are created via diffraction techniques wherein interference occurs between an illumination beam (i.e., light scattered from an object) and a reference beam (not scattered by the object) which is recorded on a recording medium. When the hologram is illuminated by the original reference beam, an observer can see the original object(s) in 3D.

patterned-retarder display – a stereoscopic display with each row having an alternating circular polarization whereby the viewer uses passive glasses to separate the left and right views by means of different circularly polarized filters for each eye.

spatially multiplexed stereo displays – A stereo display that presents the two eyes' views alternately in space (e.g., side by side).

temporally multiplexed stereo displays – a stereo display that presents the two eyes' views alternately in time.

volumetric display – A display that generates a visual representation of objects in a three-dimensional volume by controlling illumination within an (x, y, z) physical coordinate system.

TERMINOLOGY:

3D luminance – the average of the monocular luminances from both eyes and is the same as binocular luminance.

3D contrast – the average contrast from both eye views

anaglyph – a stereoscopic filtering technique for keeping separate the information delivered to the two eyes by using colored glasses, typically red versus green or red versus blue lenses in the glasses; the bandwidth of the colored filters permits only wavelengths within the given bandwidth to be passed to one or the other eye.

average stereo luminance – the average of the left and right channel luminances

binocular – as pertaining to two eyes.



binocular luminance – the combined monocular luminances of the left and right eyes, the average of the left eye monocular luminance and the right eye monocular luminance; it includes any crosstalk luminance.

binocular disparity – a lateral shift between corresponding monocular images in the two eyes.

binocular parallax – a difference in the perspective by which a scene or object is viewed by the two eyes (which creates binocular disparity).

binocular rivalry – visual suppression (i.e., loss of visibility) of image(s) in one or both eyes created by interocular inhibition owing to the viewing of dissimilar images in the two eyes.

channel – hardware and software of a display system devoted to the creation of images to be seen by one of the two eyes, either right eye or left eye.

channel luminance – the luminance generated by one of the display system's channels that does not include crosstalk luminance (some call this net luminance or intended luminance).

chromostereopsis – a subtle stereoscopic depth effect created by chromatic aberration of the eye and the differential refraction of hues of differing wavelengths; different hues are projected onto slightly different retinal locations of the two eyes which leads to a small (e.g., up to several arcmin) unintended standing disparity applied to the binocular images of an object.

crosstalk – information from one eye's view leaking into the partner eye; it creates binocular or interocular noise which degrades stereopsis; crosstalk induces the perception of what some call ghost images

crosstalk luminance – the amount of luminance from one eye's view leaking into the partner eye; some refer to it as unintended luminance.

cue – characteristics of an image (e.g., its color, shape, shading, etc.) which provide information to the visual system and brain about the properties of objects or scenes out in the world.

design eye position (DEP – also known as design eye point) – the distance between the center of the display and the point between the pupils of the eyes at which the display is designed to be viewed.

interpupillary distance – the distance between the centers of the pupils in each eye, often taken as 65 mm.

monocular – vision through one eye, either left or right, but not both at the same time; measurement made as if through one eye.

monocular luminance – luminance seen by one eye with a 3D display that is a combination of the channel luminance and the crosstalk luminance (some have called this the effective luminance).

optimal viewing distance – the distance from an autostereoscopic (auto-stereo) display at which the extinction ratio is optimal (maximum), or the leakage from one image to the other eye is minimal: Z_{OVD} .

optimal viewing position – the viewing location(s) in front of an auto-stereo display at which the extinction ratio is optimal (maximum). There might be one or multiple locations (for two-views, or multiple-views respectably). The locations are sometimes called "sweet-spots".

parallax – seeing from a different perspective; if due to having two eyes, it is called binocular parallax; if due to viewing from two different successive positions, it is called motion parallax.

stereopsis – seeing three dimensions from the cue of binocular disparity by using the two eyes together.

stereoscopic – as pertaining to stereopsis.

viewing freedom – the lateral motion range for the viewer until the extinction ratio is dropping to a predefined low acceptable value. The viewing freedom can be measured in length when the viewing distance is known, or when measured in angles (e.g., degrees).

viewing freedom offset – the angle of the optimal viewing angle from the normal view to the display.



17.1 3D LUMINANCES, CONTRASTS, & SYSTEM METRICS

In order to understand the complications that arise with 3D displays and the associated requisite terminology, it is necessary to discuss the different luminances, the kinds of useful contrasts, and some system characteristics.

3D LUMINANCES

Usually the luminance of a display is defined by a direct measurement with a light measurement device (LMD). However, in a stereo 3D display each eye is viewing a separate channel through a set of system devices; such system devices can include the eyeglasses or barrier layers of an autostereoscopic display restricting the view to one eye. Therefore, several definitions must be considered for which we will use subscripts L for the left channel (left-eye view) and R for the right channel (right-eye view)—we will use a calligraphic font to denote left and right. In the following discussion, we concentrate on the left-eye view.

1. **Channel luminance** is the intended luminance that would be observed by one eye without the crosstalk luminance (subscript “h”): L_{Lh} , L_{Rh} . Absolute channel luminance per eye is an important measure for the development stage, but not so much for the characterization of the final product. Channel luminance is never directly measured by itself unless there is no crosstalk, mixing of the left-right channel information, or a difference between the channel luminances that could have physiological impact. Additional subscripts will indicate the color of the channel (only one subscript is needed because the color of the other channel does not influence the channel luminance).
2. **Crosstalk luminance** is the undesirable luminance leakage from one eye channel to the other eye channel sometimes called unintended luminance (subscript “X”): L_{Lx} , L_{Rx} . Crosstalk luminance is also never directly measured by itself unless a black screen against which it is measured has zero-luminance. Additional subscripts will indicate the color of the channel in the opposite eye (only one subscript is needed because the color of the channel under measurement does not influence the crosstalk luminance).
3. **Monocular luminance** is the luminance seen by the observer in one of the eyes at a time and it includes the crosstalk luminance from the opposite channel. For the left eye,

$$L_L = L_{Lh} + L_{Lx}, \quad (1)$$

and for the right eye,

$$L_R = L_{Rh} + L_{Rx} \quad (2)$$

Monocular luminance is the luminance we measure with our detectors when viewing either the left- or the right-eye channel.

4. **Binocular luminance** is the arithmetic mean or average of the two monocular luminances and is the main metric we will use for stereo luminance: L_{ave} .

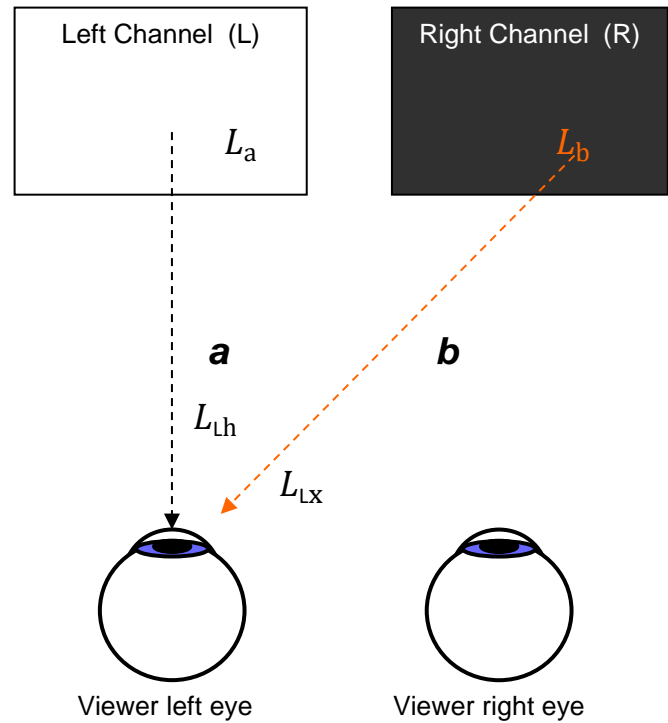


Fig. 1. Setup of stereo display. Each eye sees the channel luminance (intended) produced by its channel, L_{Lh} , plus some crosstalk luminance (unintended) from the other channel, L_{Lx}

Some prefer to use a geometric mean instead of an arithmetic mean or simple average when considering the binocular luminance:

$$\text{Geometric mean: } L_{gmean} = \sqrt{L_L L_R} \quad (3)$$

In this document, we will use the simple average for the binocular luminance:

$$\text{Arithmetic mean: } L_{ave} = \frac{L_L + L_R}{2} \quad (4)$$

Here, L_L is the monocular luminance of the left eye, and L_R is the monocular luminance of the right eye. The difference between geometric and arithmetic average is not major. For example, for luminances of $L_L = 100 \text{ cd m}^{-2}$ and $L_R = 150 \text{ cd m}^{-2}$, we get an average of 125 cd m^{-2} , whereas the geometric mean is 122.5 cd m^{-2} .

In a stereo-display, each eye views the monocular luminance, which is the channel luminance (intended, L_{Lh} or L_{Rh}) of its eye channel plus any crosstalk luminance (unintended, L_{Lx} or L_{Rx}) from the other channel. Together, these intended and unintended luminance sources contribute to the monocular luminance for a given eye. This section discusses the relationships between these luminances. In this discussion, we introduce the idea of an ideal channel luminance L_a for the left eye and L_b for the right eye that are the luminances before any attenuation is applied either by glasses or other system attenuation factors (these



luminances are also not observed) The following notation is used (see Fig. 1):

- L_a – ideal channel luminance of the left eye without attenuation from any glasses, filters, etc.,
- a – system transmission for the left channel as would occur with attenuation from glasses,
- L_b – ideal channel luminance of the right eye,
- b – system cross-transmission or fractional luminance of the right channel that produces the crosstalk that leaks into the left channel—the fraction of L_b that produces L_{Lx} that enters the left eye as would occur from the use of glasses or from some other artifact.

We will also assume that the transmission a and fractional crosstalk b are constants for all levels of gray and all colors and that the contrasts of the right and left channels are identical.

The **monocular luminance** L_{LWW} for the left eye when both left and right channels are white (white / white, with subscript “WW”) will be the channel (intended) luminance aL_{aW} plus the crosstalk (unintended) luminance, coming from the right channel bL_{bW} :

$$L_{LWW} = aL_{aW} + bL_{bW} \quad (5)$$

For this white-white configuration, the channel luminance is

$$L_{LhW} = aL_{aW}, \quad (6)$$

and the crosstalk luminance is

$$L_{LxW} = bL_{bW} \quad (7)$$

(Here, only one white w subscript is needed for the channel luminance and crosstalk luminance because their values only depend upon what is on a single left or right channel.)

Similarly, the monocular luminance L_{LKK} for the left eye when both left and right channels are black (black / black, with subscript “KK”) is

$$L_{LKK} = aL_{aK} + bL_{bK} \quad (8)$$

The channel luminance is

$$L_{LhK} = aL_{aK}, \quad (9)$$

and the crosstalk luminance is

$$L_{LxK} = bL_{bK}. \quad (10)$$

Again, only one black subscript is needed for the channel and crosstalk luminances. A similar analysis can be done for the right channel.

3D CONTRASTS

Referring to Fig. 1 above, each of the viewer’s eyes is exposed to luminance from the corresponding stereo display channel *AND* from the other stereo display channel in the form of crosstalk. Peak contrast is the ratio of the luminance from a full white level as presented by a display and the full black level from the same display. For a stereo display, the **monocular contrast** for each eye is the ratio of the white level luminance from both stereo channels, the corresponding channel and the crosstalk channel, and the

black level luminance from both stereo channels. The left-eye monocular contrast, therefore, is defined as

$$C_L \equiv \frac{L_{LWW}}{L_{LKK}}, \quad (11)$$

and the right-eye monocular contrast is defined as

$$C_R \equiv \frac{L_{RWW}}{L_{RKK}}. \quad (12)$$

For depth perception of high quality, these contrast values should be close to each other. Thus, we will define the **stereo contrast** or 3D contrast as the average of the two:

$$C \equiv \frac{C_L + C_R}{2}. \quad (13)$$

This will be a main metric to characterize the contrast of a 3D display.

3D SYSTEM METRICS

We want a metric that characterizes the **system crosstalk** produced by the luminance leakage between the two channels. Consider the left eye: The worst leakage or crosstalk should arise from the left channel being black and the right channel being white. It would be useful to take the ratio of the crosstalk luminance L_{LxW} to the white channel luminance, L_{LhW} (neither of which can we measure directly, in general). In terms of our ideal channel luminances and the transmissions, the **system crosstalk** X_L for the left eye is

$$X_L \equiv \frac{L_{LxW}}{L_{LhW}} = \frac{bL_{bW}}{aL_{aW}} \quad (14)$$

For good stereo displays, we would expect this system crosstalk to be small. The inverse of this metric is what we will call the **system contrast** C_{sysL} for the left eye.

$$C_{sysL} \equiv \frac{L_{LhW}}{L_{LxW}} = \frac{aL_{aW}}{bL_{bW}} \quad (15)$$

We want to obtain an estimate for this system contrast. To do so we will use our stereo contrast C , and assume that the monocular contrasts are both equal to the stereo contrast:

$$\text{Assume: } C = C_L = C_R \quad (16)$$

Doing this allows us to write the black ideal channel luminances in terms of the ideal white luminances:

$$L_{aK} = \frac{L_{aW}}{C} \text{ and } L_{bK} = \frac{L_{bW}}{C} \quad (17)$$

We can now write the monocular luminances in terms of only white ideal channels

$$L_{LWK} = aL_{aW} + b \frac{L_{bW}}{C}, \quad (18)$$

$$L_{LKW} = a \frac{L_{aW}}{C} + bL_{bW}, \quad (19)$$

and

$$L_{LKK} = a \frac{L_{aW}}{C} + b \frac{L_{bW}}{C} \quad (20)$$

Subtracting Eq. (19) from Eq. (5) gives



$$L_{LWW} - L_{LKW} = aL_{aW} \left(1 - \frac{1}{C}\right) \quad (21)$$

Subtracting Eq. (20) from Eq. (18) gives

$$L_{LWK} - L_{LKK} = aL_{aW} \left(1 - \frac{1}{C}\right), \quad (22)$$

which is the same as subtracting Eq. (18) from Eq. (5):

$$L_{LWW} - L_{LWK} = bL_{bW} \left(1 - \frac{1}{C}\right) \quad (23)$$

Subtracting Eq. (20) from Eq. (19) gives

$$L_{LKW} - L_{LKK} = bL_{bW} \left(1 - \frac{1}{C}\right) \quad (24)$$

Dividing Eqs. (21) by (24) gives us the **system contrast** for the left eye in Eq. (15):

$$C_{\text{sysL}} \cong \frac{L_{LWW} - L_{LKW}}{L_{LKW} - L_{LKK}} \quad (25)$$

Similarly, dividing Eqs. (22) by (24) we get another expression for the system contrast for the left eye in Eq. (15):

$$C_{\text{sysL}} \cong \frac{L_{LWK} - L_{LKK}}{L_{LKW} - L_{LKK}} \quad (26)$$

This quantity C_{sys} and the system contrast is also called the system extinction ratio or simply the *extinction ratio*, not to be confused with the extinction ratio associated with any polarizing or shutter glasses that might be used. Since both Eqs. (25) and (26) are similar, we would like to use Eq. (26) in our procedures. Values for the system contrast are larger than 1 and typically range from 5 to 500. The corresponding system crosstalk is now the reciprocal of Eq. (26),

$$X_L \cong \frac{L_{LKW} - L_{LKK}}{L_{LWK} - L_{LKK}} \quad (27)$$

Typical system crosstalk values are between 0.2 % and 20 %. Note that the expressions for the system contrast and the system crosstalk in Eqs. (26) and (27) contain measurable monocular luminances. Thus, based upon the assumption that the monocular contrasts are both the same, we have approximate expressions for the system contrast and the system crosstalk. For most displays, this should be a good approximation. Continuing with this approximation, compare the expression for the channel luminance in Eq. (6) with Eq. (21). Assuming that the contrast is large, the difference between the two expressions is small ($C^{-1} \ll 1$) and we have an approximation for the channel luminance,

$$L_{LhW} \cong L_{LWW} - L_{LKW} \quad (28)$$

Again, assuming the contrast is large, if we compare Eq. (5) with Eq. (23) we have an approximate expression for the crosstalk luminance,

$$L_{LxW} \cong L_{LKW} - L_{LKK} \quad (29)$$

Again, these expressions for the channel luminance and the crosstalk luminance contain measurable monocular luminances. Going a little further, for a quality stereo display, we might assume that the ideal channel luminances

are the same, $L_{aW} = L_{bW}$. If that is true, then an examination of Eq. (15) provides us with another approximate expression for the system contrast,

$$C_{\text{sysL}} \cong \frac{a}{b} \quad (30)$$

This system contrast C_{sysL} (left eye in this case) is a measure of the lack of crosstalk. The system crosstalk would be the reciprocal under the same approximation.

$$X_L \cong \frac{b}{a} \quad (31)$$

People refer to this X_L as the ghost-image factor or the crosstalk factor for the left eye, in this case.

In this analysis, we have only considered the left eye. The entire formalism can be repeated for the right eye. If we were to repeat the discussion for the right eye, we would draw similar conclusions:

$$C_{\text{sysR}} \cong \frac{L_{RWK} - L_{RKK}}{L_{RKW} - L_{RKK}}, \quad (32)$$

$$X_R \cong \frac{L_{RKW} - L_{RKK}}{L_{RWK} - L_{RKK}}, \quad (33)$$

$$L_{RhW} \cong L_{RWW} - L_{RWK}, \quad (34)$$

and

$$L_{RxW} \cong L_{RKW} - L_{RKK} \quad (35)$$

For good stereo displays, we would not anticipate that the left-eye performance would be dramatically different than the right-eye performance. Thus, we can define a final set of metrics that are simple averages of the above quantities:

- (1) Average system contrast (an average measure of the lack of crosstalk):

$$C_{\text{sys}} = \frac{(C_{\text{sysL}} + C_{\text{sysR}})}{2}, \quad (36)$$

- (2) Average system crosstalk (a measure of the average amount of crosstalk):

$$X = \frac{(X_L + X_R)}{2}, \quad (37)$$

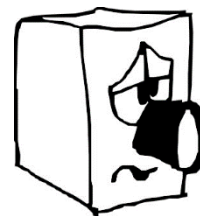
- (3) Average channel luminance:

$$L_{hW} = \frac{(L_{LhW} + L_{RhW})}{2}, \quad (38)$$

- and (4) Average crosstalk luminance:

$$L_{xW} = \frac{(L_{LxW} + L_{RxW})}{2} \quad (39)$$

All the above quantities are based upon several simplifying assumptions that should be valid for high-quality stereo displays; they are also based upon simple monocular luminance measurements for each eye view where the contrast is assumed to be similar for both the left and right channels.



I think I
need a beer.



17.2 STEREOSCOPIC DISPLAYS USING EYEGLASSES

This section deals with stereoscopic displays for which the viewer wears eyeglasses to produce the stereo effect either by polarizers, filters, or shutter glasses. Before making the measurements, the eyeglasses that are being used in the system should be checked that they perform their function adequately. There are two general categories of these glasses, passive and active. **Passive glasses** are of two general types: polarizers (either linear or circular) and color separating (anaglyph, tri-color, or multi-color - narrow band pass for each eye). **Active glasses**, based on either shutters or polarization rotation, temporally synchronize with the display's output. In all measurements the procedure will require that the same type of filters (provided by the eyeglass manufacturer) used in the 3D eyeglasses also be placed in front of the light measurement device (LMD). We only cover measurement methods that are specific to 3D displays that use glasses in this main section:

1. Eyeglasses testing
2. Stereoscopic extinction ratio & crosstalk
3. Stereoscopic contrast ratio
4. Stereoscopic luminance & luminance difference
5. Stereoscopic luminance uniformity
6. Stereoscopic color uniformity
7. Stereoscopic gray-to-gray average crosstalk
8. Stereoscopic gamma deviation
9. Stereoscopic angular behavior
10. Head tilt

Many of the measurement methods contained in the rest of this document are also applicable to 3D displays and can be adapted accordingly.

GENERAL PROCEDURAL GUIDELINES:

Figure 1 illustrates three methods for measuring the stereo display using eyeglasses. In Fig. 1(a) the LMD is fixed at the normal of the center of the display and the glasses are moved so that the LMD measures through the left and right eyes of the glasses. In Fig. 1(b) the glasses are held fixed and the LMD moves behind the left and right eyes of the glasses whereby the LMD measures two separate places on each side of the normal. In Fig. 1c the glasses are placed at the design eye position (if the manufacturer specifies such a distance) and the LMD is rotated about the center of the screen looking through each left and right eyes of the glasses whereby the same center point on the display is measured. (The interpupillary distance (IPD) is typically 65 mm.)

Fig. 1(c) represents how the eyes view the display, but in many cases there is little difference between the three methods; in such cases Fig. 1a is probably the easiest to implement. Figure 1(a) also offers the simplicity of mounting an appropriate optical polarizer or filter (supplied by the eyeglasses manufacturer) in front of the LMD to obtain the monocular measurements.

1. It is recommended to use fixtures for the LMD and attachments for holding the eyeglasses as applicable, so that the instruments will be steady during tests, and minimize noise. Hand-held LMDs should be avoided if possible.
2. We recommend the use of black shielding around the glasses and LMD to minimize stray light via reflections of the detector assembly off the display surface (see Fig. 2). A black cardboard box with opening for the eyeglasses can be a good option. If the photometer is far behind the glasses, further shielding between left and right channels by adding partition behind the glasses for left and right eyes will help prevent stray light entering the detector. These types of configurations are especially important when measuring crosstalk. All tests with the glasses should be done with the corresponding left or right side of the 3D eyeglasses placed in front of the LMD. Use an appropriate pattern to be sure

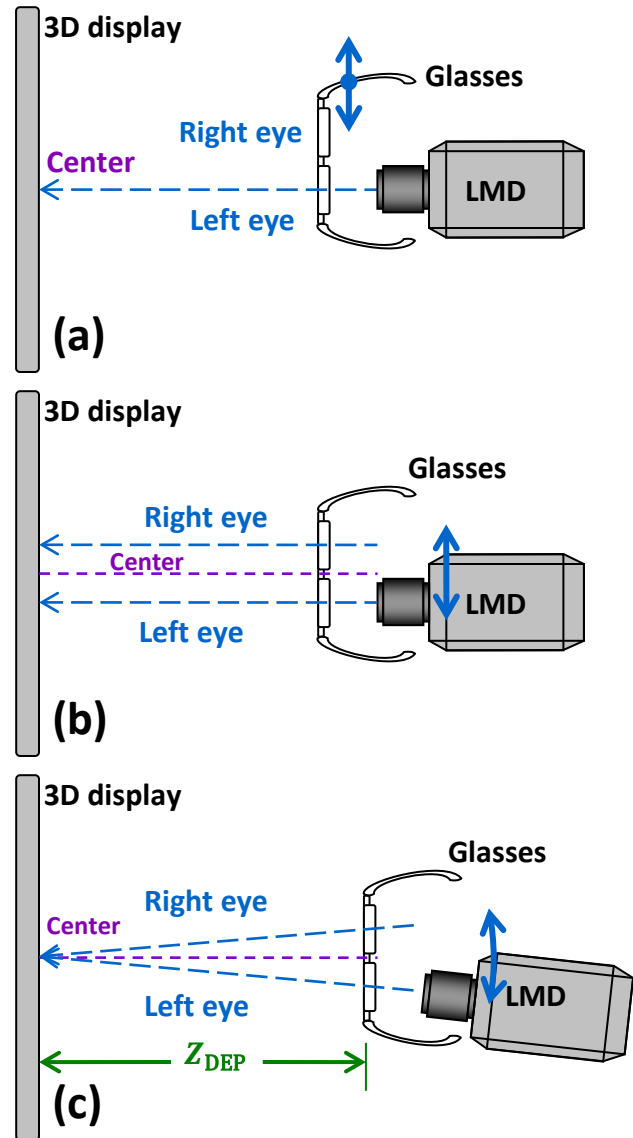


Fig. 1. Top view of setup example for testing stereo displays with glasses: (a) fixed LMD at normal, moving glasses, (b) fixed glasses, moving LMD parallel to normal (c) fixed glasses, rotating LMD about center of display.



that the display is configured to show the left-eye information in the left eye and the right-eye information in the right eye.

3. Make sure that the eyeglass lens (left or right) completely covers the LMD lens acceptance area and preferably larger.
4. Make sure that the eyeglasses are properly aligned and held horizontally and perpendicular to the DUT normal (avoiding head tilt).
5. The 3D eyeglass lenses can be stationary while the LMD is moved from behind one lens to behind the other lens.
6. In systems that are not sensitive to the viewer's location, the glasses and LMD can both be stationary. For example, in systems with linear polarizers, a rotating polarizer can be placed in front of the lens and rotated 90° for measurements involving one and then the other eye.

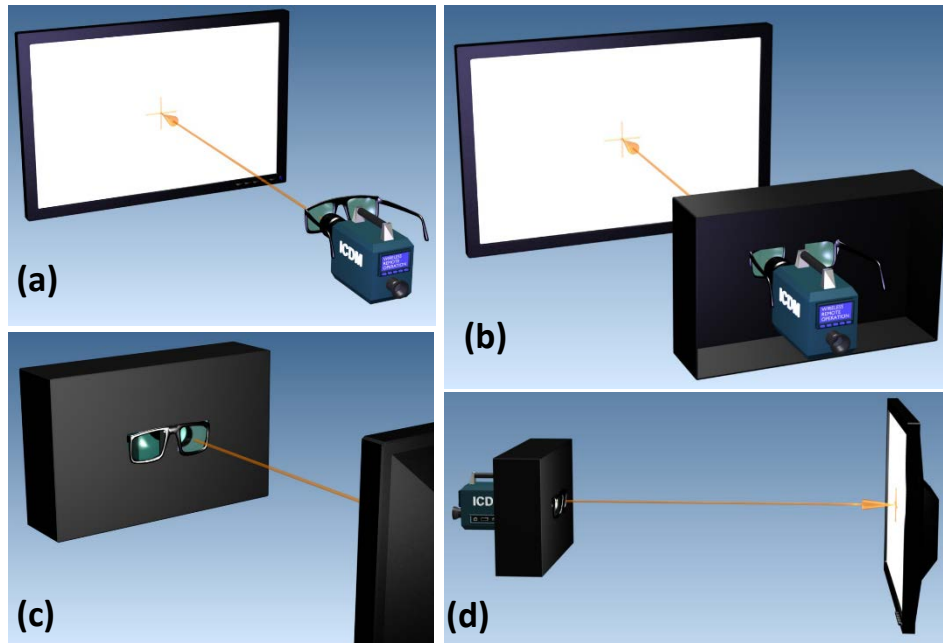
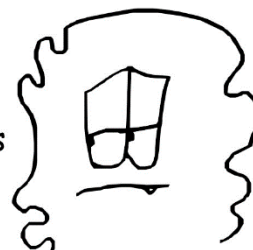


Fig. 2. Stereo measurements with black box to reduce reflections from detector and its mount: (a) without box, (b)-(d) views with box.



I've put in dummy numbers to show how it's done.



Yes, we noticed. "Sample data" wouldn't capture the essence of your contribution.



17.2.1 EYEGLASSES TESTING

Testing of the eyeglasses prior to using them in the stereo system is important. We propose two basic methods: (1) visual inspection by comparison to high-quality eyeglasses or high-quality filters, or (2) optical tests or temporal tests.

There two basic categories: (1) passive glasses (e.g. polarizers, linear or circular; color separating, anaglyphs; or multi-narrow band pass), and (2) active glasses (shutter glasses). In making these tests it is essential that the apparatus—glasses, light source, and LMD—all be rigidly held in place. Do not use handheld LMDs or DUTs for these measurements.

PASSIVE GLASSES — SIMPLE TESTING: The visual inspection of passive glasses should be made by comparing them with a reference-grade highest-quality pair of eyeglasses made for the same purpose and operating by the same principle. Put the eyeglasses to be tested behind the high-quality pair in the same orientation (one behind the other so they overlap—see Fig. 1). If both eye views through the overlap region show light transmitting at an unnoticeable change in intensity, then the tested glasses are correct for the 3D display employed.

ACTIVE GLASSES — SIMPLE TESTING: The visual inspection of active glasses should be made by comparing them with a reference-grade, highest-quality pair of eyeglasses made for the same purpose and operating by the same principle. Put one pair of glasses behind the other and make sure that the sensors (if applicable) of both glasses can see the display that is transmitting the IR signals. If both eye views through the overlap region show light transmitting at an unnoticeable change in intensity, then the tested glasses are correct for the 3D display employed.

OPTICAL TESTING OF GLASSES: Testing glasses optically, rather than comparing them as in the above, will provide you with a much better indication of their quality. But first, if you do use linear or circular polarizers, then you need to check your LMD to see if it is sensitive to the polarization state of the light it is measuring. Figure 2 shows a simple setup using a uniform, non-polarized source, and a linear polarizer.

Try several rotation angles of the polarizer over 180° and see how the LMD reading changes. It is probably unlikely that the LMD has a sensitivity to circularly polarized light, but it would not hurt to try the same experiment with circular polarizers as well, just in case. Do not place the polarizers anywhere near the uniform source so its luminance remains unaffected by close placements near its exit port. The LMD specifications may include information on polarization sensitivity too.

Visual Inspection: It is instructive to use the quality polarizer held near your eye and then examine the quality of the polarizer in the glasses when the two are crossed. You will likely see regions of nonuniformity. If the dark area is significantly dark, so that no object is visible behind it, it may indicate the suitability of the glasses for use with testing.

Linearly Polarizing Glasses: Figure 3 shows the configuration using a uniform source. Be sure to allow the uniform source to warm up before making measurements.

1. Measure the luminance L_{aligned} with the quality polarizer and glasses polarizer aligned for maximum transmitted luminance.
2. Cross the polarizers to obtain the minimum luminance and measure the luminance L_{crossed} .
3. Calculate the extinction ratio:

$$\chi_{\text{glasses}} = \frac{L_{\text{aligned}}}{L_{\text{crossed}}} \quad (1)$$

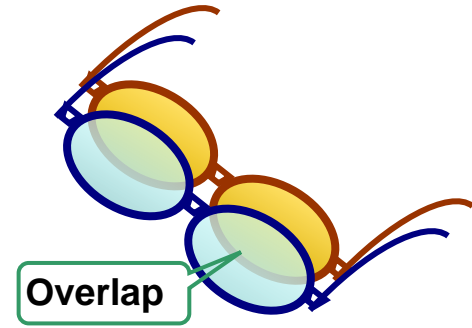


Fig. 1. Overlap region between two glasses.

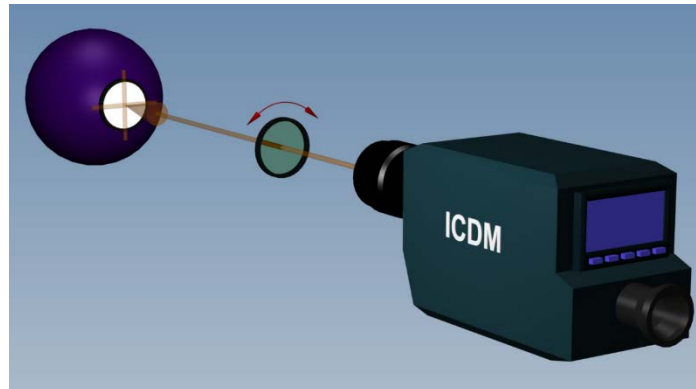


Fig. 2. Testing linear polarization sensitivity of LMD using a uniform source and a good linear polarizing filter.



Fig. 3. Testing glasses polarization quality using a uniform source and a good linear polarizing filter.



Note that if your LMD has a sensitivity to the polarization, keep the quality polarizer nearest the lens fixed and rotate the glasses.

4. Repeat the above measurement for each eye lens. Good polarizers can exhibit extinction ratios of approximately 1000:1.

Circular Polarizing Glasses: We use the arrangement in Fig. 3 only with quality circular polarizers. These circular polarizers are of two types: left-handed and right-handed. You will need to get both types of circular polarizers to test the glasses. Each eye will require one of the same circular polarization to maximize the transmitted light and the opposite combination to minimize the transmitted light. If the transmission changes dramatically as you rotate the circular polarizer then you have it backwards, flip it around; circular polarizer combinations either block or transmit, they don't act like linear polarizers if oriented correctly although color changes and small luminance changes may be observed during relative rotations.

1. Measure the luminance L_{same} for the combination that provides the most transmission.
2. Measure the luminance L_{opposite} for the combination that provides the least transmission.
3. Calculate the extinction ratio:

$$\chi = \frac{L_{\text{same}}}{L_{\text{opposite}}} \quad (2)$$

4. Repeat for the process for each eye lens of the glasses.

You may notice a little color change from slightly reddish to clear to slightly bluish as you rotate the aligned configuration. This arises because the quarter-wave plates have a wavelength dependence over the visible spectrum. They are most likely set for green light. Circular polarizers are often combinations of linear polarizers and quarter-wave plates sandwiched together, and it is the latter that has a wavelength dependence.

Colored Filter Glasses: For cases where we use multi-colors eyeglasses (either anaglyph, or multi-color) then we must use a broadband light source and our LMD must be a spectroradiometer. The setup is similar to Fig. 3 without the polarizer.

1. Without the glasses in place, measure the spectral radiance $L_s(\lambda)$ of the source.
2. Put the glasses in front of the spectroradiometer (not in front of the uniform source, stay away from its exit port) and measure the spectral radiance $L(\lambda)$ of the source through the filter.
3. The spectral transmittance of the filter is

$$\tau(\lambda) = \frac{L(\lambda)}{L_s(\lambda)} \quad (3)$$

4. Perform this measurement for each eye filter and compare the results with the manufacturing specifications.

Shutter Glasses: With temporally multiplexed 3D displays, the glasses function as shutters that synchronize with the display by means of a synchronizing signal from the display such as wireless signals like IR or RF, or hard-wired signals. The modulation could be either by amplitude or by polarization and, if the latter, the glasses only contain a switchable retarder and an analyzer. Modulation by amplitude often use a liquid crystal cell sandwiched between two polarizers.

1. Be sure that the active glasses have been activated (turned on).
2. For IR, be sure that no obstacle is between the IR sensor in the shutter glasses and the emitter on the display.
3. It is instructive to use a detector behind the glasses that is fast enough, for example an avalanche photo diode (APD) or photo-multiplier tube (PMT), to monitor the light coming through the glasses by connecting its output to an oscilloscope. With an integrating-sphere uniform source in front of the stereo display, look at the luminance signals as a function of time and verify that the periodicity matches the speed of the display (e.g., 120 Hz display would exhibit approximately 8.3 ms on and 8.3 ms off). See Fig. 4.
4. **Projection systems with passive glasses:** While the glasses are passive, there is an active optical element in front of or as part of the projection system. We have to make sure that this element is doing the same as the shutter glasses (modulation by polarization or amplitude) as described above; (a) The optical switching is performing at the correct frequency, (b) it is synchronized with the projected images, (c) the correct sequence of left and right images are shown. The projection screen needs to be polarization-preserving so if only the glasses are to be evaluated, the LMD has to be pointed in the direction of the projector and supplied with a neutral density (ND) filter and a transmissive diffuser.

The modulation of shutter glasses could be either by amplitude or by polarization and, if the latter, the glasses only contain a switchable retarder and an analyzer. Modulation by amplitude often use a liquid crystal cell sandwiched between two polarizers.

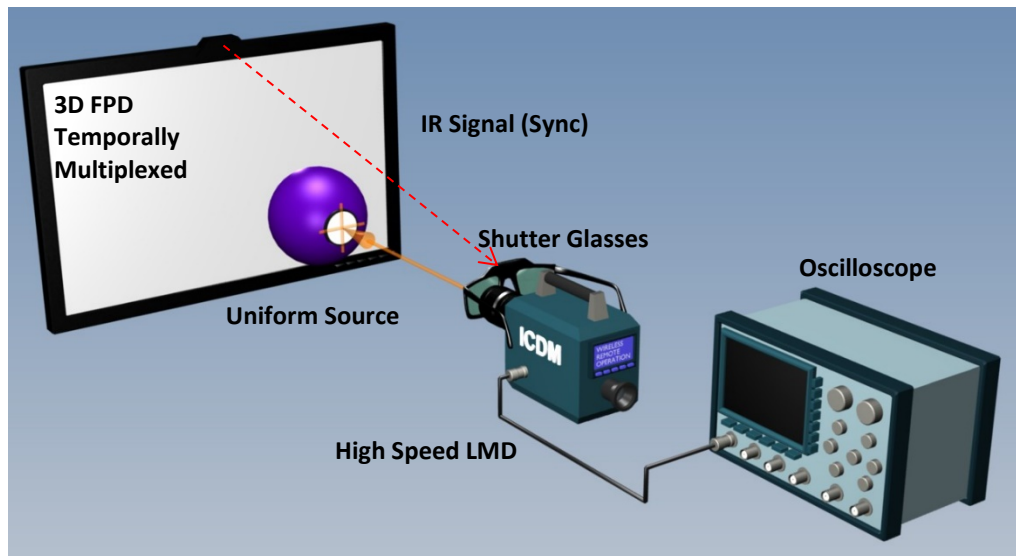


Fig. 4. Generic test setup for testing shutter glasses temporal performance with a uniform source.



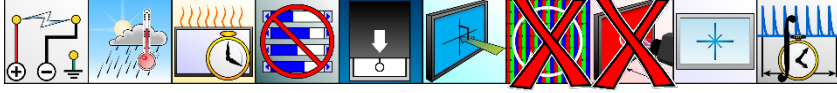
17.2.2 STEREOSCOPIC EXTINCTION RATIO & CROSSTALK

DESCRIPTION: Measure the stereoscopic extinction ratio (crosstalk between the left and right image channels) of a stereoscopic display that uses eyeglasses.

Units: none **Symbols:** X_L , X_R , χ_L , χ_R

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses of either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: (1) **Number of pixels measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects, but dead or constantly white (sub)pixels could then potentially affect the measurement result.

(2) **Angular aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). (3) **Alignment pattern:** Use an appropriate test patterns to locate the center screen and for focusing the LMD. (4) **Measurement patterns:** Provide appropriate patterns for measurements (a) white for the left eye and black for the right eye and (b) black for the left eye and white for the right eye. (5) **LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. (6) **Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.

PROCEDURE: Notation: L = left eye; R = right eye.

Left-eye luminances:

- Put the left-eye filter or left side of glasses in front of the LMD lens.
- Position the LMD at the designated eye position (DEP).
- Use test pattern with white for left eye and black for right eye.
- Measure the luminance at the display center (L_{LWK}).
- Use test pattern with black for left eye and white for right eye.
- Measure the luminance at the display center (L_{LKW}).
- Use test pattern with black for both eyes.
- Measure the luminance at the display center (L_{LKK}).



Right-Eye Luminances:

- Put the right-eye filter or right side of the glasses in front of the LMD lens.
- Position the LMD at the designated eye position (DEP).
- Use test pattern with black for left eye and white for right eye.
- Measure the luminance at the display center (L_{RKW}).
- Use test pattern with white for left eye and black for right eye.
- Measure the luminance at the display center (L_{RWK}).
- Use test pattern with black for both eyes.
- Measure luminance at the display center (L_{RKK}).



ANALYSIS: Calculate the extinction ratio at display center for the left and right eye:

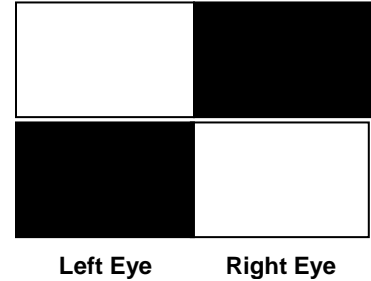
$$\chi_{\text{sysL}} = \frac{L_{LWK} - L_{LKK}}{L_{LKW} - L_{LKK}}, \chi_{\text{sysR}} = \frac{L_{RKW} - L_{RKK}}{L_{RWK} - L_{RKK}} \quad (1)$$

Calculate the crosstalk at display center for the left and right eye:

$$X_L = \frac{L_{LKW} - L_{LKK}}{L_{LWK} - L_{LKK}}, X_R = \frac{L_{RWK} - L_{RKK}}{L_{RKW} - L_{RKK}} \quad (2)$$

REPORTING: Reported the extinction ratios and cross talks to no more than three significant figures using either a number or a percentage.

COMMENTS: Light leakage between the channels is included in this measurement. This measurement result provides a characterization of crosstalk or what some call ghosting.



—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Analysis example (cd m^{-2})	
L_{LWK}	241
L_{LKW}	0.58
L_{LKK}	0.09
L_{RKW}	272
L_{RWK}	0.66
L_{RKK}	0.08
—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example	
χ_{sysL}	492
χ_{sysR}	469
X_L	0.20 %
X_R	0.21 %

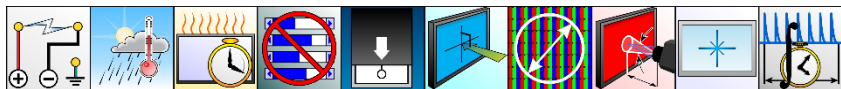


17.2.3 STEREOSCOPIC CONTRAST RATIO

DESCRIPTION: Measure the stereoscopic contrast ratios of a stereoscopic display that uses eyeglasses. **Units:** none. **Symbols:** C_L , C_R .

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses of either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: (1) **Number of pixels measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects, but dead or constantly white (sub)pixels could then potentially affect the measurement result. (2) **Angular aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). (3) **Alignment pattern:** Use an appropriate test patterns to locate the center screen and for focusing the LMD. (4) **Measurement patterns:** Provide appropriate patterns for measurements (a) white for the left eye and black for the right eye and (b) black for the left eye and white for the right eye. (5) **LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. (6) **Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.

PROCEDURE: Notation: L = left eye; R = right eye.

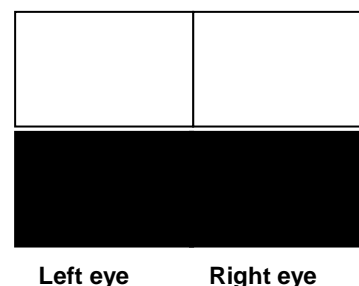
Left-eye luminances:

- Put the filter or glasses for the left eye in front of the LMD optics.
- Position the LMD at the designated eye position (DEP).
- Use test patterns for left and right eyes: (a) white/white.
- Measure the luminance at the display center (L_{LWW}).
- Use test patterns for left and right eyes: (b) black/black.
- Measure the luminance at the display center (L_{LKK}).



Right-eye luminances:

- Put the filter of the right eye in front of the LMD optics.
- Position the LMD at the designated eye position (DEP).
- Use test patterns for left and right eyes: (a) white/white.
- Measure the luminance at the display center (L_{RWW}).
- Use test patterns for left and right eyes: (b) black/black.
- Measure the luminance at the display center (L_{RKK}).



—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example (cd m^{-2})	
L_{LWW}	274.4
L_{LKK}	0.52
L_{RWW}	240
L_{RKK}	0.35
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
C_L	524
C_R	685

ANALYSIS: Calculate the stereo contrast ratios C_i ($i = L, R$) at display center for the left and right eye:

$$C_L = \frac{L_{LWW}}{L_{LKK}}, \quad (1)$$

$$C_R = \frac{L_{RWW}}{L_{RKK}} \quad (2)$$

REPORTING: The reported stereo contrast ratio is the contrast value for each channel (left and right eyes).

COMMENTS: Light leakage between the channels is included in this measurement. This measurement is done only in the display center.

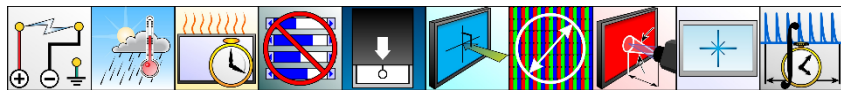
17.2.4 STEREOSCOPIC LUMINANCE & LUMINANCE DIFFERENCE

DESCRIPTION: Measure the average stereoscopic luminance of a stereoscopic display that uses eyeglasses and the luminance difference between the two eyes (channels).

Unit: cd m^{-2} . **Symbols:** $L_{\text{ave}}, L_{\text{gmean}}, \Delta L$

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses of either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (sec 3.2).



OTHER SETUP CONDITIONS: (1) **Number of pixels measured:** Usually, in practice,

we measure fewer than 500 pixels without any bad effects, but dead or constantly white (sub)pixels could then potentially affect the measurement result. **(2) Angular aperture:**

The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). **(3) Alignment pattern:** Use an appropriate test patterns to locate the center screen and for focusing the LMD. **(4) Measurement patterns:** Provide appropriate patterns for measurements (a) white for the left eye and black for the right eye and (b) black for the left eye and white for the right eye. **(5) LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. **(6) Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.



PROCEDURE: Notation: L = left eye; R = right eye.

Left-eye luminances:

1. Put the left-eye filter or left side of glasses in front of the LMD lens.
2. Position the LMD at the designated eye position (DEP).
3. Use test patterns for left and right eyes: (a) white/white.
4. Measure the luminance at the display center (L_{LWW}).
5. Use test pattern with black for left eye and white for right eye.
6. Measure the luminance at the display center (L_{LKW}).



Right-eye luminances

7. Put the right-eye filter or right side of the glasses in front of the LMD lens.
8. Position the LMD at the designated eye position (DEP).
9. Use test patterns for left and right eyes: (a) white/white. 
10. Measure the luminance at the display center (L_{RWW}).
11. Use test pattern with white for left eye and black for right eye. 
12. Measure the luminance at the display center (L_{RWK}).



ANALYSIS:

1. Calculate the channel (subscript “h”) luminances of the left channel and the right channel:

$$L_{\text{LhW}} = L_{\text{LWW}} - L_{\text{LKW}} \text{ and } L_{\text{RhW}} = L_{\text{RWW}} - L_{\text{RWK}} \quad (1)$$

2. Calculate the average stereo luminance (L_{ave}) and geometric mean:

$$L_{\text{ave}} = \frac{L_{\text{LhW}} + L_{\text{RhW}}}{2} \text{ and } L_{\text{gmean}} = \sqrt{L_{\text{LhW}} L_{\text{RhW}}} \quad (2)$$

- 3.** Calculate the relative luminance difference (ΔL) between the two channels (left and right eyes):

$$\Delta L = \frac{|L_{LhW} - L_{RhW}|}{\min(L_{LhW}, L_{RhW})} \quad (3)$$

REPORTING: Report the channel luminances, average stereo luminance, and luminance difference to no more than three or four significant figures. The luminance difference may be reported as a number or a percentage.

COMMENTS: None.

Left eye	Right eye
<p>1. <i>Left eye</i></p> <p>2. <i>Left eye</i></p> <p>3. <i>Left eye</i></p> <p>4. <i>Left eye</i></p> <p>5. <i>Left eye</i></p> <p>6. <i>Left eye</i></p> <p>7. <i>Left eye</i></p> <p>8. <i>Left eye</i></p> <p>9. <i>Left eye</i></p> <p>10. <i>Left eye</i></p> <p>11. <i>Left eye</i></p> <p>12. <i>Left eye</i></p> <p>13. <i>Left eye</i></p> <p>14. <i>Left eye</i></p> <p>15. <i>Left eye</i></p> <p>16. <i>Left eye</i></p> <p>17. <i>Left eye</i></p> <p>18. <i>Left eye</i></p> <p>19. <i>Left eye</i></p> <p>20. <i>Left eye</i></p> <p>21. <i>Left eye</i></p> <p>22. <i>Left eye</i></p> <p>23. <i>Left eye</i></p> <p>24. <i>Left eye</i></p> <p>25. <i>Left eye</i></p> <p>26. <i>Left eye</i></p> <p>27. <i>Left eye</i></p> <p>28. <i>Left eye</i></p> <p>29. <i>Left eye</i></p> <p>30. <i>Left eye</i></p> <p>31. <i>Left eye</i></p> <p>32. <i>Left eye</i></p> <p>33. <i>Left eye</i></p> <p>34. <i>Left eye</i></p> <p>35. <i>Left eye</i></p> <p>36. <i>Left eye</i></p> <p>37. <i>Left eye</i></p> <p>38. 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<p>12. <i>Right eye</i></p> <p>13. <i>Right eye</i></p> <p>14. <i>Right eye</i></p> <p>15. <i>Right eye</i></p> <p>16. <i>Right eye</i></p> <p>17. <i>Right eye</i></p> <p>18. <i>Right eye</i></p> <p>19. <i>Right eye</i></p> <p>20. <i>Right eye</i></p> <p>21. <i>Right eye</i></p> <p>22. <i>Right eye</i></p> <p>23. <i>Right eye</i></p> <p>24. <i>Right eye</i></p> <p>25. <i>Right eye</i></p> <p>26. <i>Right eye</i></p> <p>27. <i>Right eye</i></p> <p>28. <i>Right eye</i></p> <p>29. <i>Right eye</i></p> <p>30. <i>Right eye</i></p> <p>31. <i>Right eye</i></p> <p>32. <i>Right eye</i></p> <p>33. <i>Right eye</i></p> <p>34. <i>Right eye</i></p> <p>35. <i>Right eye</i></p> <p>36. <i>Right eye</i></p> <p>37. <i>Right eye</i></p> <p>38. <i>Right eye</i></p> <p>39. <i>Right eye</i></p> <p>40. <i>Right eye</i></p> <p>41. <i>Right eye</i></p> <p>42. <i>Right eye</i></p> <p>43. <i>Right eye</i></p> <p>44. <i>Right eye</i></p> <p>45. <i>Right eye</i></p> <p>46. <i>Right eye</i></p> <p>47. <i>Right eye</i></p> <p>48. <i>Right eye</i></p> <p>49. <i>Right eye</i></p> <p>50. <i>Right eye</i></p> <p>51. <i>Right eye</i></p> <p>52. <i>Right eye</i></p> <p>53. <i>Right eye</i></p> <p>54. <i>Right eye</i></p> <p>55. <i>Right eye</i></p> <p>56. <i>Right eye</i></p> <p>57. <i>Right eye</i></p> <p>58. <i>Right eye</i></p> <p>59. <i>Right eye</i></p> <p>60. <i>Right eye</i></p> <p>61. <i>Right eye</i></p> <p>62. <i>Right eye</i></p> <p>63. <i>Right eye</i></p> <p>64. <i>Right eye</i></p> <p>65. <i>Right eye</i></p> <p>66. <i>Right eye</i></p> <p>67. <i>Right eye</i></p> <p>68. <i>Right eye</i></p> <p>69. <i>Right eye</i></p> <p>70. <i>Right eye</i></p> <p>71. <i>Right eye</i></p> <p>72. <i>Right eye</i></p> <p>73. <i>Right eye</i></p> <p>74. <i>Right eye</i></p> <p>75. <i>Right eye</i></p> <p>76. <i>Right eye</i></p> <p>77. <i>Right eye</i></p> <p>78. <i>Right eye</i></p> <p>79. <i>Right eye</i></p> <p>80. <i>Right eye</i></p> <p>81. <i>Right eye</i></p> <p>82. <i>Right eye</i></p> <p>83. <i>Right eye</i></p> <p>84. <i>Right eye</i></p> <p>85. <i>Right eye</i></p> <p>86. <i>Right eye</i></p> <p>87. <i>Right eye</i></p> <p>88. <i>Right eye</i></p> <p>89. <i>Right eye</i></p> <p>90. <i>Right eye</i></p> <p>91. <i>Right eye</i></p> <p>92. <i>Right eye</i></p> <p>93. <i>Right eye</i></p> <p>94. <i>Right eye</i></p> <p>95. <i>Right eye</i></p> <p>96. <i>Right eye</i></p> <p>97. <i>Right eye</i></p> <p>98. <i>Right eye</i></p> <p>99. <i>Right eye</i></p> <p>100. <i>Right eye</i></p>

<p>—SAMPLE DATA ONLY—</p> <p>Do not use any values shown to represent expected results of your measurements.</p>	
<p>Analysis example (cd m^{-2})</p>	
L_{LWW}	240
L_{LKW}	0.49
L_{RWW}	274.4
L_{RWK}	0.58

<p>—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.</p>	
<p>Reporting example (cd m⁻²)</p>	
L_{LhW}	239.5
L_{RhW}	273.8
L_{ave}	256.7
L_{gmean}	256.1
ΔL (%)	14.3%

17.2.5 STEREOSCOPIC LUMINANCE SAMPLED UNIFORMITY

ALIAS: sampled luminance uniformity, sampled luminance nonuniformity

DESCRIPTION: Measure the stereoscopic luminance sampled uniformity of a stereoscopic display that uses eyeglasses. As sample points use the centers of a 3×3 matrix that covers the screen. **Unit:** %. **Symbol:** \mathcal{U} .

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses of either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§3.2).

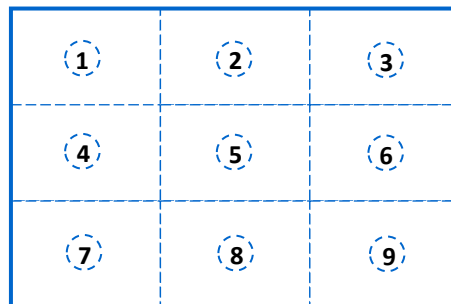
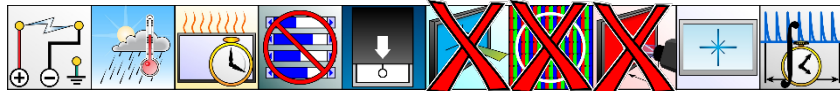
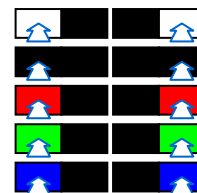


Fig. 1. Location of measurement points. Location #5 is the center of the screen.

OTHER SETUP CONDITIONS: (1) **Number and location of pixels measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects, but dead or constantly white (sub)pixels could then potentially affect the measurement result. (2) **Angular aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). (3) **Alignment pattern:** Use an appropriate test pattern to locate the center screen, to establish left and right channels, and to locate the n selected sample points $n = 5$ or $n = 9$. (4) **Measurement patterns:** The channel (eye view) that is not measured should have full-screen black images. Provide appropriate full-screen patterns for measurements (left-right notation): for the left eye, WK, KK, RK, GK, BK; and for the right eye, KW, KK, KR, KG, KB. (5) **LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated- or design-eye position so that it can be rotated to view all the locations. (6) **Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.



PROCEDURE: Measure the monocular luminance L_{LQi} for the left-eye channel of a full-screen color $Q = W, K, R, G, B$ (also measure the chromaticity coordinates if you will be looking at the chromaticity uniformity as in the next section) with the right eye channel black; measure at each selected point $i = 1, 2, \dots, n$ with $n = 5$ for the four corners and center (points 1, 3, 5, 7, & 9) or $n = 9$ for all nine points; do this for each pattern for the left-eye channel. Make similar measurement for the right-eye view, L_{ROi} with the left eye channel black.

ANALYSIS: In the following we use the notation: $\mathcal{E} = \text{L, R}$ is the left or right eye view and Q denotes the color of the full-screen pattern $Q = \text{W, K, R, G, B}$ (white, black, red, green, blue) in the eye channel under measurement where the opposite eye channel is black.

1. For each full-screen color $Q = W, K, R, G, B$ determine the minimum and maximum luminances:

$$L_{\mathcal{E}Q_{\max}} = \max_{i=1,2,\dots,n} L_{\mathcal{E}Q_i}; \text{ and } L_{\mathcal{E}Q_{\min}} = \min_{i=1,2,\dots,n} L_{\mathcal{E}Q_i} \quad (1)$$

2. Calculate the uniformity for each display pattern: $\mathcal{U}_{\varepsilon Q} = \frac{L_{\varepsilon Q_{\min}}}{L_{\varepsilon Q_{\max}}}$ (2)

3. Calculate the average uniformity for both eyes, for each color $Q = \text{W, K, R, G, B}$: $u_Q = \frac{u_{LQ} + u_{RQ}}{2}$ (3)

4. The nonuniformity is $\mathcal{N} = 1 - \frac{L_{EQ\min}}{L_{EQ\max}}$ (4)

REPORTING: Report as a number or percentage the stereoscopic luminance uniformity and nonuniformity for each eye (left, right), for each of the colors (white, black, red, green, and blue), and the average uniformity for both eyes for each of the primary colors.

COMMENTS: This measurement is similar to standard uniformity measurement (of a non-stereo display). Light leakage between the channels is minimized in this test, since we choose black for the other eye. This allows verification of the uniformity of each channel (eye). It helps to identify if one channel has excess non-uniformity. The average of both eyes gives an idea of the general uniformity (for each color).

<p>—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.</p>	
<p>Reporting example for $Q = W$</p>	
\mathcal{U}_{LW}	80%
\mathcal{U}_{RW}	86%
\mathcal{U}_W	83%

17.2.6 STEREOSCOPIC CHROMATICITY UNIFORMITY

DESCRIPTION: Measure the stereoscopic chromaticity uniformity of a stereoscopic display that uses eyeglasses. **Units:** none. **Symbols:** $\Delta u'v'$.

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses that can be either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: (1) **Angular aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). (2) **Alignment pattern:** Use an appropriate test pattern to locate the center screen, for focusing the LMD, to establish left and right channels, and to locate the n selected sample points $n = 5$ or $n = 9$. (3) **Measurement patterns:** The channel (eye view) that is not measured should have full-screen black images. Provide appropriate full-screen patterns for measurements (left-right notation): for the left eye, WK, KK, RK, GK, BK; and for the right eye, KW, KK, KR, KG, KB. (4) **LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. (5) **Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.

PROCEDURE: Measure the chromaticity (CIE- u' , CIE- v') for the left-eye channel of a full-screen color $Q = W, K, R, G, B$ (you may have obtained such measurements from the previous measurement section) with the right eye channel black; measure at each selected point $i = 1, 2, \dots, n$ with $n = 5$ for the four corners and center (points 1, 3, 5, 7, & 9) or $n = 9$ for all nine points; do this for each pattern for the left-eye channel. Make similar measurement for the right-eye channel of color Q with the left eye channel black.

ANALYSIS: In the following we use the notation: $\mathcal{E} = \text{L, R}$ is the left or right eye view and Q denotes the color of the full-screen pattern $Q = \text{W, K, R, G, B}$ (white, black, red, green, blue) in the eye channel under measurement where the opposite eye channel is black. For each left-channel full-screen color

$\bar{Q} = W, K, R, G, B$, calculate the Euclidean distances $\Delta u'v'$ between all two pairs $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n$ with $i \neq j$ of the 5 or 9 points measured:

$$\Delta u'v'_{\text{LQ}ij} = \sqrt{(u'_{\text{LQ}i} - u'_{\text{LQ}j})^2 + (v'_{\text{LQ}i} - v'_{\text{LQ}j})^2} \quad (1)$$

Repeat the calculation for the right-eye channel.

$$\Delta u'v'_{\text{RQ}ij} = \sqrt{(u'_{\text{RQ}i} - u'_{\text{RQ}j})^2 + (v'_{\text{RQ}i} - v'_{\text{RQ}j})^2} \quad (2)$$

Determine the maximum $\Delta u'v'$ for each eye and for each color Q :

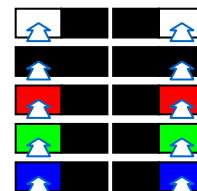
$$\Delta u'v'_{\mathcal{L}Q_{\max}} = \max_{i,j=1,2,\dots,n;i \neq j} \Delta u'v'_{\mathcal{L}Q_{ij}} \text{ and } \Delta u'v'_{\mathcal{R}Q_{\max}} = \max_{i,j=1,2,\dots,n;i \neq j} \Delta u'v'_{\mathcal{R}Q_{ij}} \quad (3)$$

REPORTING: Report all maximum values of $\Delta u'v'$ for each eye and for each color O .

COMMENTS: Light leakage between the channels is minimized in this test, since we choose black for the other channel. In this way each chromaticity measurement verifies the chromaticity uniformity of predominantly one channel at a time. Shielding with black box between the channels (left and right eyes) could help to minimize stray light. Chromaticity measurements for black uniformity in very low light levels is a challenge and therefore is optional.

1	2	3
4	5	6
7	8	9

Fig. 1. Location of measurement points. Location #5 is the center of the screen.



—SAMPLE DATA ONLY—				
Do not use any values shown to represent expected results of your measurements.				
Example for white, left channel				
9pt	5pt	L_L	u'	v'
1	1	373.0	0.1919	0.4658
2		466.1	0.1921	0.4675
3	3	477.3	0.1917	0.4667
4		415.7	0.1922	0.4692
5	5	553.4	0.1922	0.4691
6		493.8	0.1921	0.4704
7	7	412.6	0.1911	0.4639
8		496.9	0.1913	0.4676
9	9	492.1	0.1911	0.4668

<p>—SAMPLE DATA ONLY—</p> <p>Do not use any values shown to represent expected results of your measurements.</p>	
<p>Reporting example for white left channel</p>	
$\Delta u'v'_{lQ_{\max}}$	0.007



17.2.7 STEREOSCOPIC GRAY-TO-GRAY AVERAGE CROSSTALK

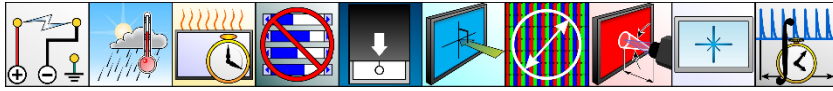
ALIAS: Ghost Imaging, gray-to-gray stereoscopic crosstalk

DESCRIPTION: We measure the crosstalk between left and right eye channels for all combinations of a set of gray levels of a stereoscopic display that uses eyeglasses.

Units: none. **Symbols:** X_L , X_R

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use eyeglasses that can be either circular or linear polarization, shutter glasses, or color separation glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2)



OTHER SETUP CONDITIONS: (1) **Number of Pixels Measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects, but dead or constantly white (sub)pixels could then potentially affect the measurement result.

(2) **Angular aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). (3) **Alignment pattern:** Use an appropriate test pattern to locate the center screen, for focusing the LMD, and establish left and right channels. (4) **Measurement patterns:** Patterns will be provided so that each eye will see a full gray screen at a gray level (V_L and V_R , L for left eye, R for right eye) selected from $n = 9$ equidistant input levels from black to white ($V_i = 0, 31, 63, 95, 127, 159, 191, 223, 255$, for $i = 1, 2, \dots, 9$) or from $n = 5$ levels (0, 63, 127, 191, 255, for $i = 1, 2, \dots, 5$) depending upon your needs. See chapter 6 Gray-Scale & Color-Scale Metrics for the appropriate selection of gray levels should five or nine levels not be suitable for your needs. For any set of n gray levels we will be measuring the luminance for each pair of levels V_{Li} and V_{Rj} for $i = 1, 2, \dots, n$, and $j =$

1, 2, ..., n . In the notation L_{Lij} or L_{Rij} the left index i refers to the pattern for the left eye, and the index j refers to the pattern for the right eye; the left index always refers to the left eye, and the right index always refers to the right eye. Thus, $L_{L0,255} \equiv L_{Lkw}$ employs left-black and right-white patterns, and $L_{R0,255} \equiv L_{Rwk}$ employs left-white and right-black patterns. (5) **LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. (6) **Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.

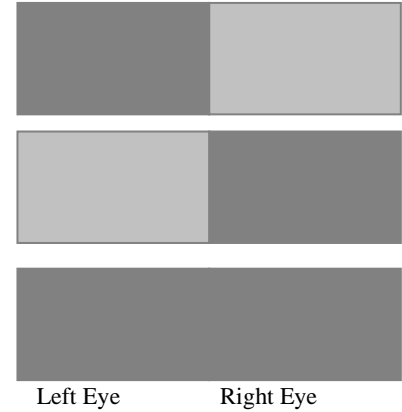
PROCEDURE:

- Put the appropriate filter for the left eye in front of the LMD lens.
- Measure the luminance L_{Lij} at the display center for all combinations of gray levels (V_{Li} , V_{Lj}) in each eye, $i = 1, 2, \dots, n$, and $j = 1, 2, \dots, n$, including $i = j$.
- Put the appropriate filter of the right eye in front of the LMD lens.
- Measure the luminance L_{Rij} at the display center for all combinations of gray levels (V_{Ri} , V_{Rj}) in each eye, $i = 1, 2, \dots, n$, and $j = 1, 2, \dots, n$, including $i = j$.

ANALYSIS: Calculate the gray-to-gray

stereoscopic crosstalk X_{Lij} for any two gray levels V_{Li} and V_{Lj} ($i \neq j$) at display center for the left eye. Perform the same calculation for the 3D crosstalk X_{Rij} for any two gray levels V_{Ri} and V_{Rj} ($i \neq j$) at display center for the right eye.

$$X_{Lij} = \left| \frac{L_{Lij} - L_{Lii}}{L_{Lji} - L_{Lii}} \right|, i \neq j. \quad (1)$$



Left Eye Right Eye

—SAMPLE DATA ONLY (Full data)—					
Do not use any values shown to represent expected results of your measurements.					
Data example: Luminance for the left eye: L_{Lij} (cd m ⁻²), $n = 5$					
$V_{Lj} \rightarrow$ $V_{Li} \downarrow$	0	63	127	191	255
0	0.0264	0.0511	0.197	0.536	0.871
63	2.71	4.01	4.68	5.25	5.41
127	18.0	19.3	21.3	22.5	23.7
191	46.7	48.1	48.4	51.2	52.1
255	67.0	75.2	78.0	79.7	81.4



$$X_{Rij} = \left| \frac{L_{Rij} - L_{Rjj}}{L_{Rji} - L_{Rjj}} \right|, i \neq j. \quad (2)$$

Calculate the average, standard deviation, and maximum of for all the left eye crosstalk values X_{Lij} and all the right eye crosstalk values X_{Rij} : X_{Lave} , σ_{XL} , X_{Lmax} , X_{Rave} , σ_{XR} , X_{Rmax} .

—SAMPLE DATA ONLY (Full data)—					
Do not use any values shown to represent expected results of your measurements.					
Analysis example for the left eye					
$V_{Lj} \rightarrow$ $V_{Li} \downarrow$	0	63	127	191	255
0	0%	0.92%	0.95%	1.09%	1.26%
63	32.8%	0%	4.38%	2.81%	1.97%
127	15.4%	11.9%	0%	4.05%	4.31%
191	8.96%	6.68%	9.64%	0%	3.23%
255	17.9%	8.13%	5.86%	5.87%	0%
X_{Lave}	7.41%	σ_{XL}	7.65%	X_{Lmax}	32.8%

—SAMPLE DATA ONLY (Simplified data)—					
Do not use any values shown to represent expected results of your measurements.					
Analysis example for the left eye					
X_{Lave}	7.41%	σ_{XL}	7.65%	X_{Lmax}	32.8%

REPORTING: Report the average, standard deviation, and the maximum crosstalk for both eyes to no more than three significant figures. Use either numbers or percentages.

COMMENTS: When n gray levels are used the number of crosstalk evaluations is $n(n - 1)$ for each eye. In this measurement we use the display gray levels as adjusted by the manufacturer (in most cases the electro-optical transfer function is a power function with the exponent $\gamma = 2.2$).



17.2.8 STEREOSCOPIC GAMMA DEVIATION

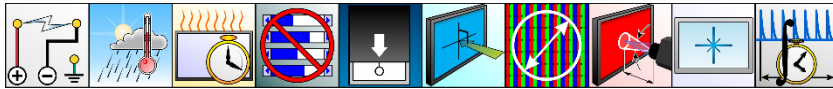
DESCRIPTION: We measure the gray scales (electro-optical transfer function assumed to follow a power law with the exponent γ) of left and right image channels (eyes) for all combinations of a selected set of nine or five gray levels for a stereoscopic display that uses eyeglasses.

Units: none. **Symbols:** $\gamma_L, \gamma_R, g_L, g_R$

This is a binocular application of the gamma distortion metrics discussed in chapter 6 Gray-Scale and Color-Scale Metrics. This stereoscopic-gamma-deviation metric determines how the gray shades of one eye channel are affected by the gray shades in the other eye channel and it selects the left and right eye worst case for reporting the gamma deviation.

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic displays that use glasses that can be either circular or linear polarization, shutter glasses, or color separation glasses.

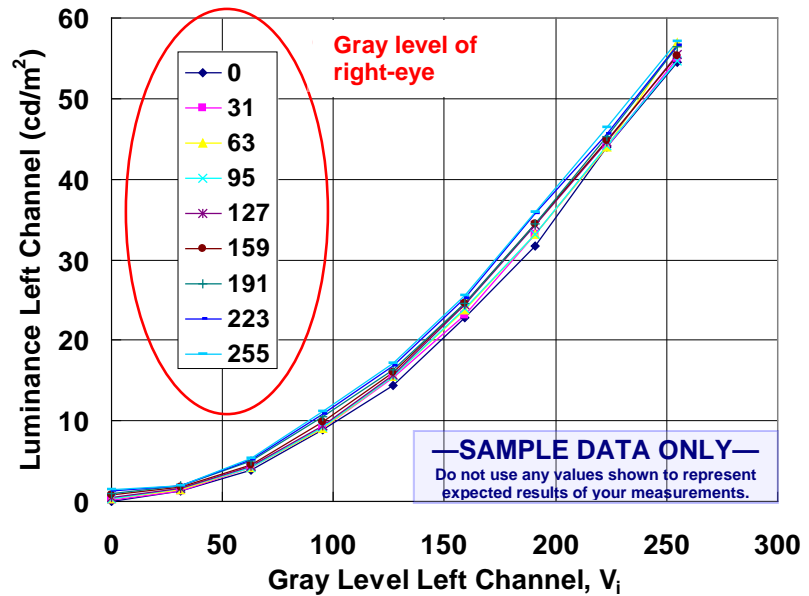
SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: (1) **Number of pixels measured:** Usually, in practice, we measure fewer than 500 pixels without any bad effects, but dead or constantly white (sub)pixels could then potentially affect the measurement result. (2) **Angular aperture:** The angular aperture must be less than or equal to 1° so that the lens of the LMD better simulates the room-light pupil size of the eye (5 mm). (3) **Alignment pattern:** Use an appropriate test pattern to 1) locate the center screen, 2) focus the LMD, and 3) establish the left and right channels. (4) **Measurement patterns:** Patterns will be provided so that each eye will see a full gray screen at a gray level (V_L and V_R , L for left eye, R for right eye) selected from $n = 9$ levels from black to white ($V_i = 0, 31, 63, 95, 127, 159, 191, 223, 255$, for $i = 1, 2, \dots, 9$) or from $n = 5$ levels (0, 63, 127, 191, 255, for $i = 1, 2, \dots, 5$) depending upon your needs. See chapter 6 Gray-Scale & Color-Scale Metrics for the appropriate selection of gray levels should five or nine levels not be suitable for your needs. A total of 81 measurements will be made for each eye channel if nine levels are used, 25 measurements per eye if five levels are used. (5) **LMD location:** If there is a manufacturer-specified location for obtaining the best 3D experience, then place the LMD at that designated or design eye position. (6) **Filters or glasses:** The LMD should have filters (or glasses) in front of its lens that match the right/left filters of the glasses used for viewing the display. The filters can be either two polarizers with different orientation of linear or circular polarization, two shutter glasses that are synchronized with the displayed left and right images, or two different color filters (e.g., with red/blue for anaglyph, or different narrow band-pass filters for color separation). If the display system product (DUT + glasses) is to be evaluated, the supplied glasses shall be used.

PROCEDURE:

1. Put the filter of the left eye in front of the LMD lens.
2. Measure the luminances $L_{Li,j}$ at the display center for each left-eye full-screen pattern at gray level V_i , $i = 1, 2, \dots, 9$, with the right full-screen pattern at gray levels V_j , $j = 1, 2, \dots, 9$, where i is the index of the gray level for the left eye and j is the index for the gray level of the right eye. For $n = 9$ levels this requires $n^2 = 81$ luminance measurements.
3. Put the filter of the right eye in front of the LMD lens.
4. Measure the luminances $L_{Ri,j}$ at the display center for each right-eye full-screen pattern at gray level V_i , $i = 1, 2, \dots, 9$, with the left full-screen pattern at gray levels V_j , $j = 1, 2, \dots, 9$, where i is the index of the gray level for the right eye and j is the index for the gray level of the left eye. For $n = 9$ levels, this requires $n^2 = 81$ luminance measurements.





ANALYSIS: We calculate the gamma values for left and right eye by performing a log-log straight line fit based upon the model

$$L(V_i) = a(V_i - V_K)^\gamma + L_K, \quad (1)$$

where $V_K = 0$ usually. See § 6.3 Log-Log Gamma Determination for full details. We fit the following function to the gray-scale data:

$$\log[L(V_i) - L_K] = \gamma \log(V_i - V_K) + \log a. \quad (2)$$

The fit provides values γ and $b = \log a$, for $i = 1, 2, \dots, n$ for an n -level gray scale.

Left-eye gammas: For each right-eye gray level V_{Rj} , $j = 1, 2, \dots, n$, determine γ_{Lj} and b_{Lj} by a log-log fit [Eq. (2)] of the left-eye gray scale $L_L(V_{Li})$, $i = 1, 2, \dots, n$, according to the above prescription and record the gamma values γ_{Lj} .

Right-eye gammas: For each gray left-eye gray level V_{Lj} , $j = 1, 2, \dots, n$, determine γ_{Ri} and b_{Ri} by a log-log fit [Eq. (2)] of the right-eye gray scale $L_R(V_{Ri})$, $i = 1, 2, \dots, n$, according to the above prescription and record the gamma values: γ_{Ri} .

Gamma deviation: The gamma deviation of left eye, g_L , and right eye, g_R , can be defined as the difference between maximum and minimum gamma values for each channel.

$$g_L = \max_{j=1,2,\dots,n} \gamma_{Lj} - \min_{j=1,2,\dots,n} \gamma_{Lj}, \quad (3)$$

and

$$g_R = \max_{i=1,2,\dots,n} \gamma_{Ri} - \min_{i=1,2,\dots,n} \gamma_{Ri}. \quad (4)$$

REPORTING: Report stereoscopic gamma deviation for right eye and left eye to no more than three significant figures.

COMMENTS: Using more gray levels (smaller intervals) may provide better results if needed.

—SAMPLE DATA ONLY—									
Do not use any values shown to represent expected results of your measurements.									
Analysis example for the left eye									
$V_{Lj} \downarrow \backslash V_{Lj} \rightarrow$	0	31	63	95	127	159	191	223	255
0	0.02125	0.1858	0.2594	0.3239	0.4558	0.7568	1.042	1.228	1.421
31	1.298	1.338	1.48	1.572	1.608	1.841	1.957	1.992	2.001
63	3.826	4.124	4.211	4.24	4.395	4.539	5.033	5.203	5.343
95	8.911	9.038	9.045	9.268	9.377	9.788	10.44	10.76	11.17
127	14.33	15.42	15.48	15.57	15.65	15.95	16.33	16.79	17.15
159	22.79	23.13	23.84	23.88	24.4	24.57	24.64	25.2	25.56
191	31.64	33.11	33.13	33.23	34.32	34.37	34.44	35.71	35.87
223	43.94	44.01	44.04	44.19	44.71	44.8	45.35	45.59	46.35
255	54.51	54.95	56.94	54.63	55.52	55.29	56.46	56.65	57.01
Gamma values	1.81	1.85	1.84	1.82	1.86	1.89	1.94	2.02	2.13
Gamma deviation	0.32								

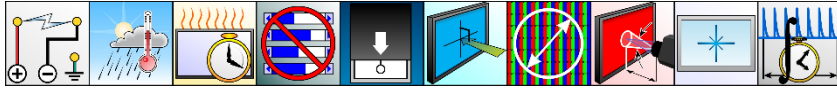


17.2.9 STEREOSCOPIC ANGULAR BEHAVIOR

ALIAS: Viewing-angle behavior, viewing-direction behavior

DESCRIPTION: Stereoscopic behavior over angles. All the measurements in the previous sections (luminance, crosstalk, uniformity of luminance and colors) should be repeated for several viewing directions over the useful range as specified by agreement between the supplier and customer.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

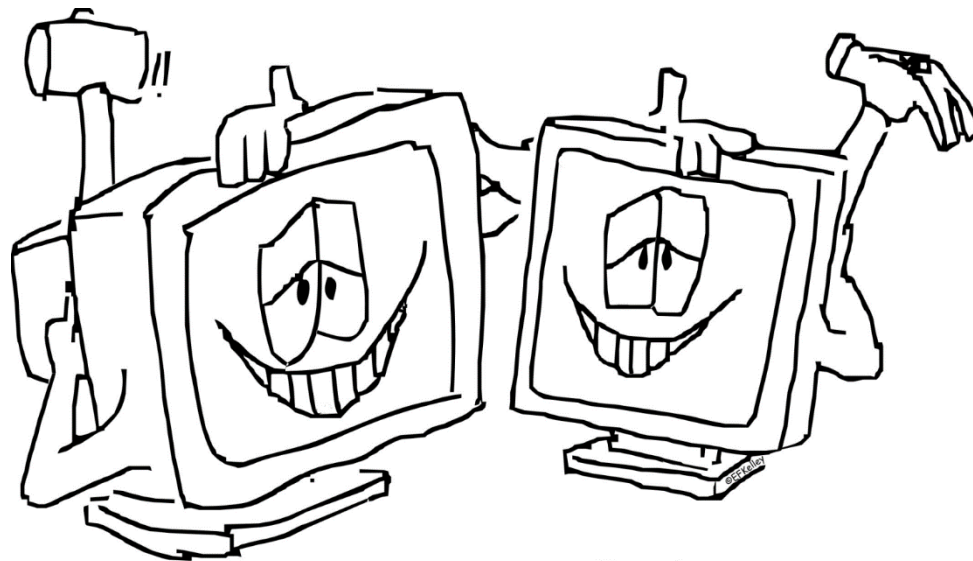


PROCEDURE: Repeat all above measurements when the LMD is positioned at several designated eye positions that reflect the useful range of angles with respect to the DUT normal (mostly in the horizontal plane, but also some positions in the vertical).

ANALYSIS: Repeat the analysis of all previous paragraphs.

REPORTING: Report the luminance, crosstalk, uniformity of luminance and colors, for all selected designated eye positions. In all cases report the angles relative to normal.

COMMENTS: Light leakage between the channels is minimized in this test, since we choose black for the other channel. In this way each color measurement verifies the color uniformity of predominantly one channel at a time.



BUDDIES!

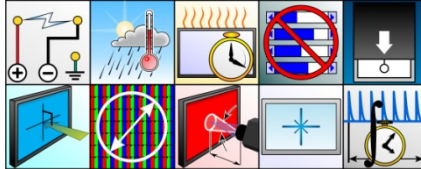
(If you understand this cartoon, you might be dating yourself.)



17.2.10 HEAD TILT

DESCRIPTION: Stereoscopic behavior as a function of the angle of rotation around the viewing direction (Z-axis) can be important. This test is especially important for eyeglasses with linear polarizers when tilting the head from side-to-side (a roll angle ν from the horizontal orientation). All the measurements in the previous sections (luminance, crosstalk, uniformity of luminance and colors) can be repeated for several tilt angles of the eyeglasses or the filters over the useful range as specified by the manufacturer. This test is important for 3D displays that employ linear polarizers, but it can be used with all 3D displays that use glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



PROCEDURE:

Repeat all above measurements when the LMD is positioned at the manufacturer-specified eye position, for several tilt angles of the eyeglasses relative to the nominal orientation (e.g. roll about the display Z-axis, ν in Fig. 2). Measurements that are more important are: (1) crosstalk over tilt angles, and (2) luminance over tilt angles

ANALYSIS: Repeat the analysis of the previous paragraphs.

REPORTING: Report the crosstalk, luminance, and optionally the uniformity of luminance and colors, for few tilt angles of the eyeglasses.

COMMENTS: These measurements should be done mostly for displays with linear polarizing eyeglasses. Tilt angles between 5° and 15° are reasonable to use. Besides the effect of reduced stereo extinction ratio, the tilt is also causing reduced luminance and distortion due to conversion of horizontal disparity (used for stereopsis) to vertical disparity. This generates discomfort and eye fatigue over time. Here are some sample data for a variety of tilt angles of the glasses.

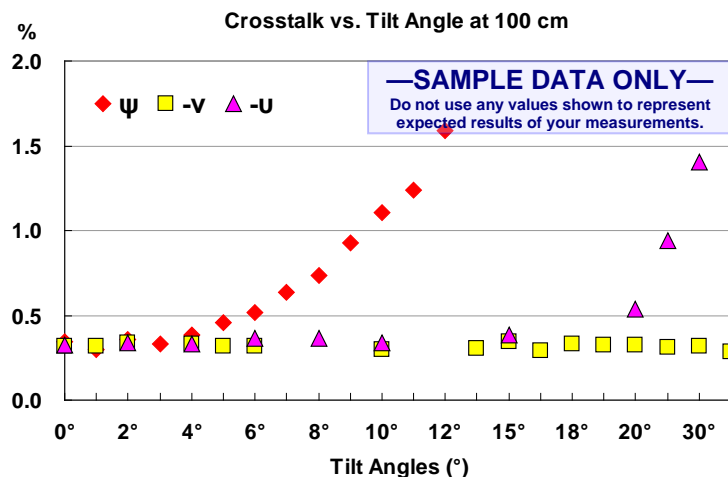


Fig. 3. Sample data for three independent rotations of the glasses.

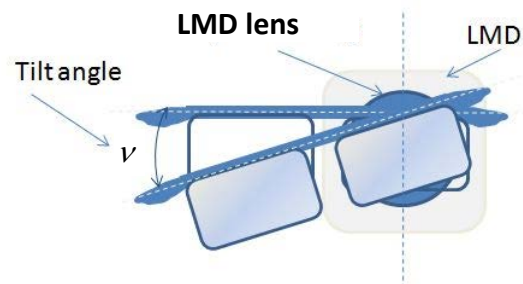


Fig. 1. Looking toward the LMD from the location of the display illustrating the tilt angle.

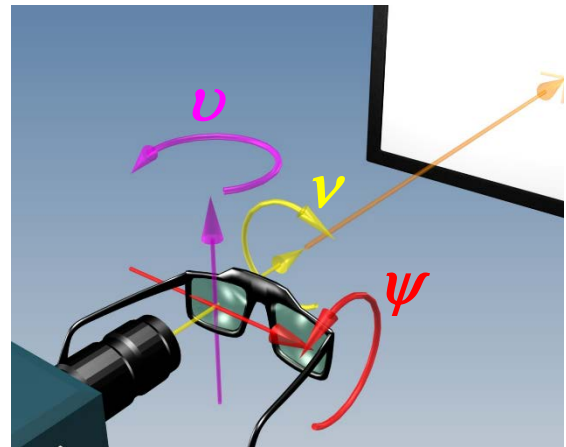


Fig. 2. Rotation axes parallel to the axis of the display (X, Y, Z) coordinate axes with their direction of rotation according to the right-hand screw rule.

Tilt Angle	ψ	$-\nu$	$-u$
0°	0.34	0.32	0.32
1°	0.29	0.32	
2°	0.36	0.33	0.33
3°	0.33		
4°	0.38	0.33	0.33
5°	0.45	0.31	
6°	0.51	0.31	0.36
7°	0.63		
8°	0.73		0.36
9°	0.92		
10°	1.10	0.29	0.34
11°	1.23		
12°	1.59		
13°		0.30	
15°		0.34	0.38
17°		0.29	
18°		0.33	
19°		0.32	
20°		0.32	0.53
25°		0.30	0.94
30°		0.318	1.407
35°		0.285	



17.2.11 Gray to Gray Lightness Crosstalk

DESCRIPTION: Measurement of 3D stereoscopic crosstalk between the two channels (left eye and right eye) as proposed in section 17.2.7 reports the luminance crosstalk. However, this does not correspond to the *perceived* luminance difference, *i.e.* the lightness difference. Here we propose to include several mid-gray level combinations, and to analyze the data in a way that is closer to the human eye perception (this work is based on Ref. 1).

Units: none; **Symbol:** $X_{r,c}$ – renormalized lightness crosstalk units.

APPLICATION: All stereoscopic displays with glasses.

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



OTHER SETUP CONDITIONS: The measurement set-up is shown in Figure 2. A luminance meter is directed perpendicularly towards the center on the display surface. The 3D glasses are mounted in front of the luminance meter with the meter measuring through one of the lenses. The glasses should be mounted in a position that is similar to the position of the glasses with respect to the eyes of a person wearing them when watching the 3D display.

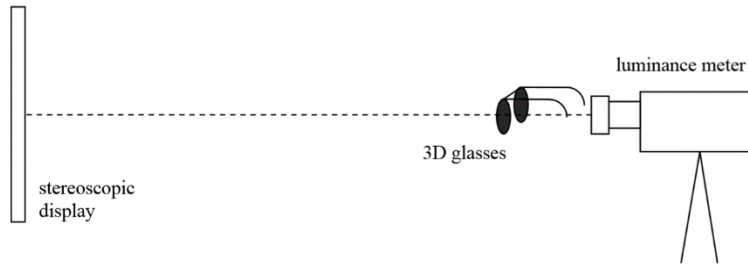


Fig. 2. Measurement set-up for 3D crosstalk characterization.

PROCEDURE:

1. Use the LMD as in Fig. 2 – aimed at the center of the stereoscopic display, and focused on the DUT through the one of the lenses of the eyeglasses (e.g. the left lens)
2. Drive the display with combination of left and right images as described in (5) below. The observed image (left eye) will be driven with gray level $V_{\text{obs},i}$, while the unobserved image will be driven with gray level $V_{\text{unobs},j}$, $i \neq j$
3. The measurements should be done to a combination of levels i , and j ; $i, j = 0, 1, 2 \dots n$ where $V_{\text{obs},0}$ and $V_{\text{unobs},0}$ are the black level and $V_{\text{obs},N}$ and $V_{\text{unobs},N}$ are the white level.
4. The number of gray levels n can be 17, so that there will be 17×17 combinations. However, it will be sufficient to use only $n = 9$ per eye, so that there will be 9×9 combinations.
5. For the 9×9 combinations, the input gray levels will be: 0, 31, 63, 95, 127, 159, 191, 223 and 255. The value of 0 corresponds to full black and 255 to full white.
6. For each combination of $V_{\text{obs},i}$ and $V_{\text{unobs},j}$, measure the luminance through one lens, and record it for the analysis in the combination table shown to the right in Fig. 3.
7. In the table, the rows correspond to the values of the unobserved image and the columns to the values of the observed image.

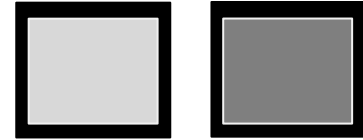
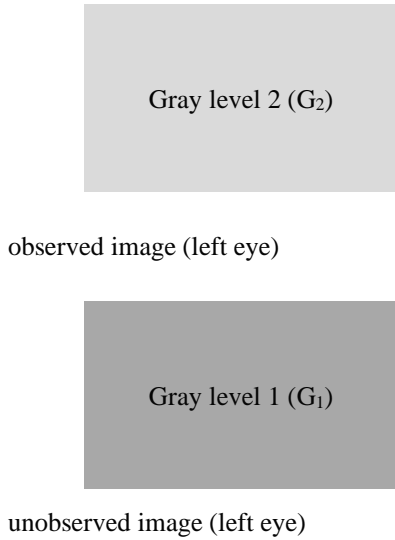


Fig. 1. 3D test images (left/right)



Observed image

	G ₀	G ₁	G ₂	G ₃	G ₄	G ₅	G ₆	G ₇	G ₈
G ₀	0.22	0.31	1.4	3.5	8.1	14	23	35	50
G ₁	0.23	0.42	1.9	4	9.1	14	23	35	50
G ₂	0.24	0.51	1.5	4.1	8.6	15	25	38	51
G ₃	0.26	0.47	1.8	3.8	8.3	15	27	37	50
G ₄	0.32	0.57	1.6	3.8	8.2	15	24	37	50
G ₅	0.43	0.51	1.3	4.2	8.1	14	23	34	48
G ₆	0.59	0.62	1.5	4.6	8.3	14	23	34	46
G ₇	0.9	0.87	1.5	3.2	9	14	23	33	46
G ₈	1.4	1.4	1.8	3.4	8.7	15	23	33	46

Unobserved image

Fig. 3. Example of stimulus for 3D crosstalk characterization (left) and the corresponding luminance measurement grid for 9 gray-level combinations for the observed and unobserved images (right)

ANALYSIS:

1. Conversion to renormalized lightness values: For any cell of coordinate r, c , (where r and c is the grey level index of the unobserved and observed test image, respectively) in the measurement grid, the conversion from luminance to 8-bit renormalized lightness values (0...255) is expressed by the following formula:

$$L_{r,c} = \frac{255}{100} \left(116 f \left(\frac{Y_{r,c} - Y_{0,0}}{Y_{N,N} - Y_{0,0}} \right) - 16 \right) \quad (1)$$

where

$$f(x) = \begin{cases} x^{\frac{1}{3}}, & x > \left(\frac{6}{29}\right)^3 \\ \frac{1}{3} \left(\frac{29}{6}\right)^2 x + \frac{4}{29}, & \text{otherwise} \end{cases} \quad (2)$$

Where: $Y_{r,c}$ is the luminance in each cell as measured by the luminance meter, $L_{r,c}$ is the corresponding renormalized lightness, $Y_{0,0}$ is the luminance of the lowest grey level (“black offset”) and $Y_{N,N}$ the luminance of the full white at the highest grey level N .

2. Report the calculated values of $L_{r,c}$ in the results table. See example in Fig. 4 (left).
3. An alternative grey level scheme for $L_{r,c}$ is a simplified formula with a pure power law:

$$L_{r,c} = 255 \left(\frac{Y_{r,c} - Y_{0,0}}{Y_{N,N} - Y_{0,0}} \right)^{\frac{1}{\gamma}} \quad (3)$$

The exponent γ^{-1} can be discussed. We propose to use 2.2^{-1} because, although 2.4^{-1} is a closer match to the overall CIE 1976 L^* lightness function, 2.2^{-1} is a better match where it matters most, *i.e.* for low light values.

4. Based on either step 1, or step 3, we will get a table of lightness combinations $L_{r,c}$ (see Fig. 4 – left side) renormalized to 255. Note that these values are *not* the CIE 1976 L^* lightnesses.
5. In each column in Fig. 4 (left side) subtract the number in the diagonal and round the numbers to integers. For numbers above the diagonal reverse the sign. The crosstalk then becomes:

$$X_{r,c} = \text{sgn}(r - c) \text{rnd}(L_{r,c} - L_{c,c}) \quad (4)$$



6. Convert this table of crosstalk numbers to a color-coded table, with blue colors for positive numbers and red for negative, black is for zeros. Naturally, the diagonal will be black. (See Fig. 4 – right)

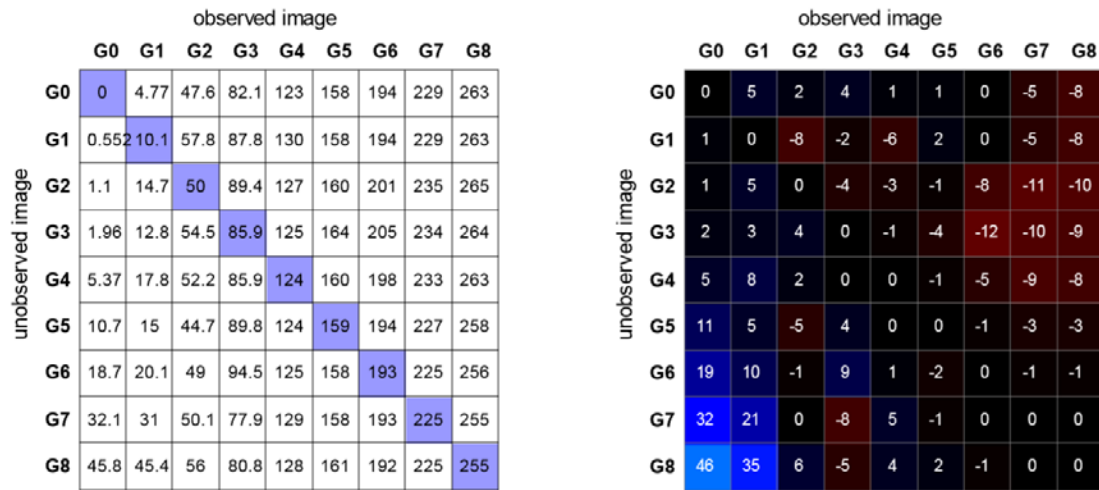


Fig. 4. Measurement grid converted to renormalized lightness (left) and final crosstalk representation as a grid of renormalized lightness differences (right).

REPORTING: Report the final crosstalk values $X_{r,c}$ in a table format (Fig. 4, right)

COMMENTS: None.

REFERENCE:

- [1] H. Van Parys *et al.* “Characterization of 3D Gray-to-Gray Crosstalk with a Matrix of Lightness Differences”, paper 12-2, *SID Proceedings*, pages 133-136 (2012).



17.3 AUTOSTEREOSCOPIC DISPLAYS WITH TWO VIEWS

Autostereoscopic displays provide a three-dimensional (3D) experience without the need of eyeglasses. However, the position of the viewer is restricted in space so that each eye sees one of two views that in combination produce the stereoscopic effect.

The autostereoscopic displays can be one of the following types: **(1) Two views:** one viewer at one location (“sweet spot”), where one view is for each eye, when the two views—desired visible points—are aiming the two eyes. **(2) Multiple of the two-views:** A display where multiples of the two-views are generated and allow 3D-stereo viewing at multiple optimal viewing locations (sweet spots). These are covered in the next main section (§ 17.3.6 Autostereoscopic displays with multiple views) **(3) Light-field Displays:** multiple views in almost continuous viewing locations (sweet spots)—details will follow in § 17.4.6 Autostereoscopic light-field displays.

The pair of views is generated by one of several optical means:

1. **Barrier lines:** Show certain pixels to one eye and hide them from the other eye. The barrier lines are usually in front on the display at a specified gap. They could also be behind the display and direct the backlight illumination (for LCDs) to either of the eyes (Fig. 1).
2. **Lenticular lenses:** Focus certain pixels to one eye, and other pixels to the other eye (Fig. 2).
3. **Barrier lines 2D/3D switchable:** Barrier lines in front of the display made by a separate LCD surface. The odd or even vertical lines can be activated to generate a 3D-stereo separation to the two eyes or become clear to switch to a two-dimensional mode (similar to Fig. 3 where the barrier layer is an LCD surface).
4. **Lenticular special lenses:** Lenticular lenses implemented with other methods rather than traditional (curved) lenses. This could be LC cells with local driving, graded index materials, or any other optical means to have optical effect similar to the lenticular lenses. In case of LC local cells, the ability of 2D/3D switchable is possible.
5. **Temporal backlighting:** Temporal variable lighting in the backlight of an LCD, which in each frame direct the light to one of two orientations, which match the locations of the two eyes.
6. **Light-field displays:** These are implemented with tiny lenslets or lenticular lenses as will be explained later.

An example explaining the geometry for front barrier layer is described in Fig. 3. (Not anaglyph) At the optimum viewing distance and proper location of the eyes (viewer head) the red pixels (for example) are viewed by the right (R) eye, and the blue pixels (for example) are viewed by the left (L) eye. The optimum viewing location for this condition is sometimes colloquially referred to as the “sweet spot.” The separation between the eyes is called interpupillary distance (IPD). For adults it is typically 6.25 cm (some use 6.5 cm). An angular scan of the illumination in front the barrier layer will show the behavior of the beams coming from the display including the barrier layer separation. A typical scan is shown in Fig. 4. When the red pixels are on, we get the luminance plotted in red, which is optimized for the left eye. When the blue pixels are on, we get the blue curve. The optimum location for the eyes (L, R) is denoted at the bottom Fig. 4. This optimum viewing location (or “sweet spot”) is the average location between the eyes, the center of the forehead of the viewer. In some displays it is not exactly normal to the display but has an offset, as shown by the dotted line in Fig. 4. To find the best viewing location for two view stereo displays we will look on Fig. 5.

The rays coming through the barrier layers are limited in range. They define the viewing freedom, which is how far the eyes can move left or right from the optimum viewing location (“sweet spot”) and still have optimal perception of depth. When the viewer is positioned further or closer to the display from the optimum distance, the viewing freedom is narrowed.

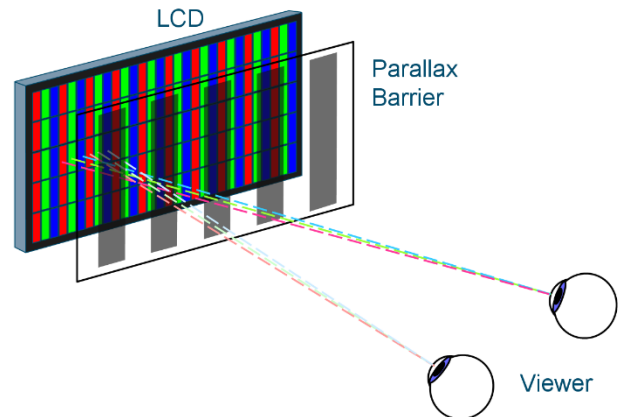


Fig. 1. Autostereoscopic display with front parallax barrier. The barrier is shown semitransparent for illustration purposes. In reality it is opaque.

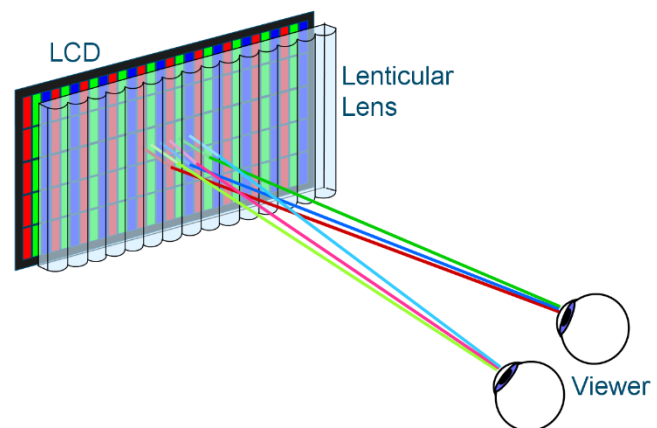


Fig. 2. Autostereoscopic display with lenticular lenses.



This is marked in Fig. 5 by the shaded area with a diamond shape. The extreme forward and backward points of the range defining the viewing range.

The description of the viewing freedom above is for two views. However, it can be expended for multi-views, so that in space we get several diamond shaped regions for each optimum viewing location node (sweet spot).

It is important to measure the angular behavior of the auto stereoscopic (auto-stereo) display, in order to specify its viewer position, and the freedom to move around this point (or multiple points in multi-views). The measurement can be done with either of the following tools:

- Use an LMD with small aperture, mounted on a rotation scanning stage. The rotation axis should be around the center of the measured display with the LMD focused on the display. The angular aperture of the LMD should be smaller than the scanned rotation steps by at least x5, and it depends on the length of the scanning stage.
- Conoscopic camera focused on the display, and with angular resolution at least five times smaller than the angular steps to be measured.

More details on the instrument requirements are specified in each of the test procedures which follow, especially in the tests related to angular measurements.

This chapter deals with stereoscopic displays in which the viewer is positioned in one location, the designated eye position (DEP), and there is no need for eyeglasses. Measurement methods that are covered in this main section are:

1. Autostereoscopic system crosstalk
2. Autostereoscopic stereo contrast ratio
3. Autostereoscopic luminance
4. Autostereoscopic luminance uniformity
5. Autostereoscopic angular range.

All measurements are made from the designated eye position (DEP), which is the location designed to obtain the best stereo image quality and is usually close to the normal of the screen. The test distance should be similar to the optimum viewing distance. There is no need for any accessory in front of the light measurement device (LMD). The lens of the LMD should be focused on the display surface. Because of the possible sensitivity to the size of the measurement-field angle (MFA), we recommend that the MFA be $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$.

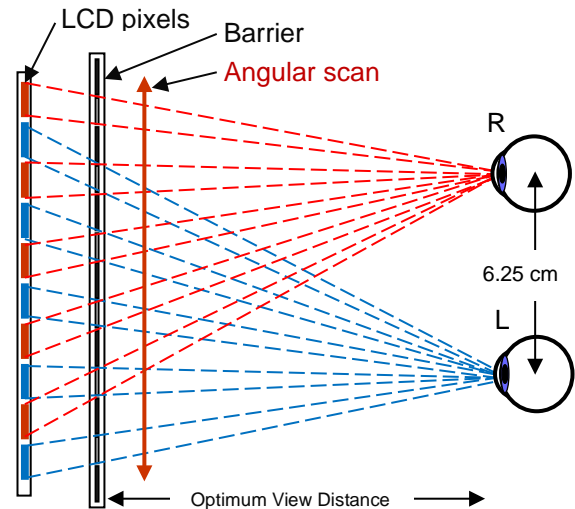


Fig. 3. Autostereoscopic display with barrier layer in front of the pixels.

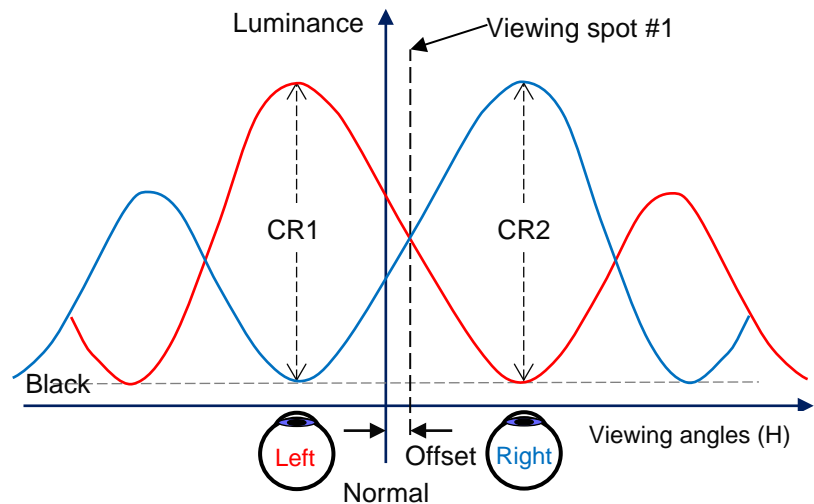


Fig. 4. Autostereoscopic display viewing scan showing offset for optimum viewing.

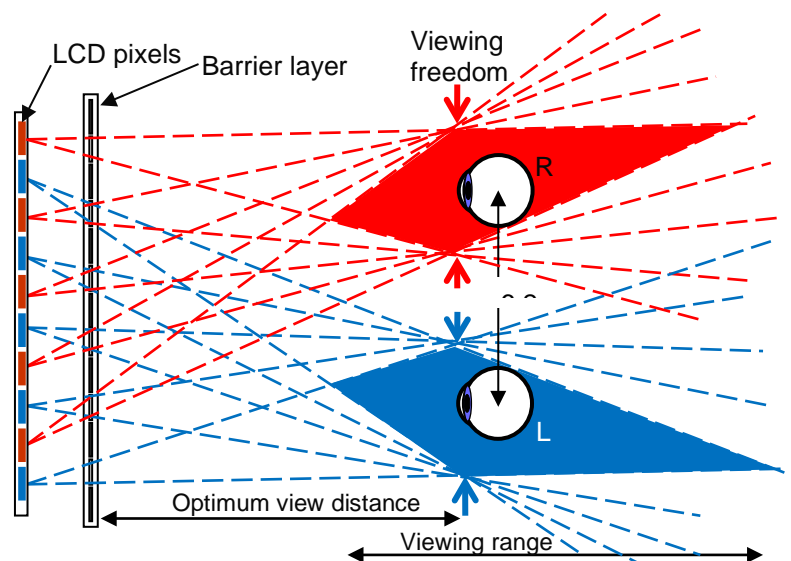


Fig. 5. Autostereoscopic viewing range and freedom.



17.3.1 TWO-VIEW AUTOSTEREOSCOPIC SYSTEM CROSSTALK

ALIAS: ghost image, stereo crosstalk

DESCRIPTION: Measure the stereoscopic system crosstalk of a two-view autostereoscopic display at the display center (with or without eye-tracking).

Units: none. **Symbols:** X_L , X_R .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. Test patterns to be used are two-view images designated left eye/right eye: (a) black/black, (b) black/white, (c) white/white, and (d) white/black.

PROCEDURE: The designated eye position (DEP) is z_{DEP} . The interpupillary distance (IPD) is Δx_{IPD} . Recall that measurements are to be made at center screen. For displays with eye-tracking the function must be disabled.

1. Place the LMD at the position of left eye: $x = -\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
2. Measure the luminances of the test patterns for the left eye for the following pattern definitions: (a) black/white, L_{LKW} , (b) white/black, L_{LWK} , (c) black/black, L_{LKK} .
3. Set the LMD at the position of right eye: $x = +\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
4. Measure the luminance of the test patterns for right eye for the following (a) black/white, L_{RKW} , (b) white/black, L_{RWK} , (c) black/black, L_{RKK} .

ANALYSIS:

Calculate the crosstalk X_L and X_R equivalent values use the following equations:

$$X_L = \frac{L_{LKW} - L_{LKK}}{L_{LWK} - L_{LKK}} \quad (1)$$

$$X_R = \frac{L_{RWK} - L_{RKK}}{L_{RWK} - L_{RKK}} \quad (2)$$

Optionally, calculate the system contrast C_{sysL} and C_{sysR} with the maximum values of luminance for each eye, for a two-view stereoscopic display you can use the following equations:

$$C_{sysL} = \frac{L_{LWK} - L_{LKK}}{L_{LKW} - L_{LKK}} \quad (3)$$

$$C_{sysR} = \frac{L_{RWK} - L_{RKK}}{L_{RWK} - L_{RKK}} \quad (4)$$

Note that these are reciprocals of the crosstalk.

REPORTING: The 3D system crosstalk values X_L and X_R for the left and right eyes.

COMMENTS: Light leakage between the channels is included in these measurements.

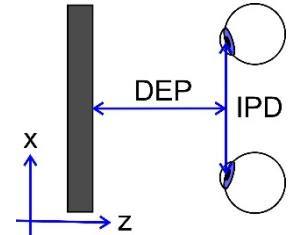
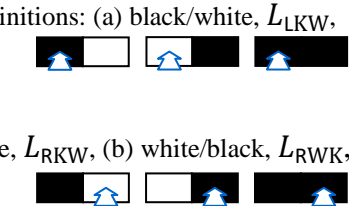


Fig. 1. Design eye position and interpupillary distance.



—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Analysis example (cd m ⁻²)	
L_{LKW}	3.9
L_{LWK}	161.1
L_{LKK}	0.23
L_{RWK}	4.9
L_{RKW}	154.9
L_{RKK}	0.13

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example	
X_L	2.3%
X_R	3.1%



17.3.2 TWO-VIEW AUTOSTEREOSCOPIC CONTRAST RATIO

DESCRIPTION: Measure the stereoscopic contrast ratio of a two-view autostereoscopic display at center point on display panel (with or without eye-tracking).

Units: none. **Symbols:** C_L , C_R .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. Test patterns to be used are: (a) two-view black images (black/black, K/K) and (a) two-view white images (white/white, W/W).

PROCEDURE: The designated eye position (DEP) is z_{DEP} . The interpupillary distance (IPD) is Δx_{IPD} . Recall that measurements are to be made at center screen.

1. Place the LMD at the position of left eye: $x = -\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
2. Measure the left-eye luminance L_{LWW} for the white/white pattern.
3. Measure the left-eye luminance L_{LKK} for the black/black pattern.
4. Set the LMD at the position of right eye: $x = +\Delta x_{IPD}/2$, $y = 0$, $z = z_{DEP}$.
5. Measure right-eye luminance L_{RWW} for the white/white pattern.
6. Measure right-eye luminance L_{RKK} for the black/black pattern.

ANALYSIS: Calculate the stereo contrast ratio (C_L , C_R) at designate positions in the display center for the left eye and right eye:

$$C_L = \frac{L_{LWW}}{L_{LKK}} \quad (1)$$

$$C_R = \frac{L_{RWW}}{L_{RKK}} \quad (2)$$

REPORTING: Stereoscopic contrast ratios C_L and C_R for the left and right eye views.

COMMENTS: Light leakage between two-view displays is included in these measurements.

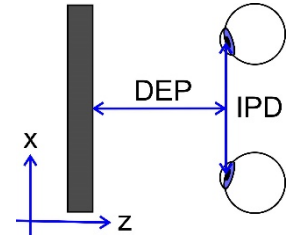


Fig. 1. Design eye position and interpupillary distance.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example (cd m ⁻²)	
L_{LWW}	169.3
L_{LKK}	0.23
L_{RWW}	156.4
L_{RKK}	0.13

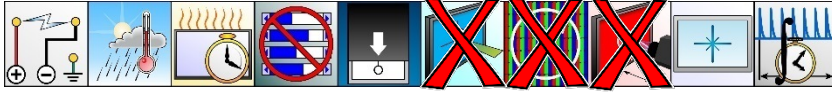
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
C_L	736
C_R	1203



17.3.3 TWO-VIEW AUTOSTEREOSCOPIC LUMINANCE

DESCRIPTION: Measure the average luminance of a two-view autostereoscopic display at the center of the display (with or without eye-tracking). **Unit:** cd m^{-2} . **Symbols:** L_L , L_R .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. Test patterns to be used are two-view images designated left eye/right eye: (a) black/black and (b) white/white.

PROCEDURE: The designated eye position (DEP) is z_{DEP} . The interpupillary distance (IPD) is Δx_{IPD} . Recall that measurements are to be made at center screen.

1. Place the LMD at the position of left eye: $x = -\Delta x_{\text{IPD}}/2$, $y = 0$, $z = z_{\text{DEP}}$
2. Measure the luminance L_{LWW} for the white/white pattern.
3. Set the LMD at the position of right eye: $x = +\Delta x_{\text{IPD}}/2$, $y = 0$, $z = z_{\text{DEP}}$
4. Measure the luminance L_{RWW} for the white/white pattern.

ANALYSIS: Calculate the average luminance L_{ave} as:

$$L_{\text{ave}} = \frac{L_{\text{LWW}} + L_{\text{RWW}}}{2} \quad (1)$$

REPORTING: Reported stereoscopic luminance value.

COMMENTS: Light leakage between two-view displays is included in these measurements. In Eq. (1) we are using a linear average of the two-view luminance for display system. Perceived factor will not be included. Do not refer to this as “brightness”! This is luminance, not brightness!

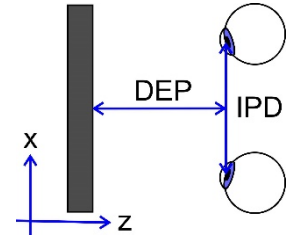


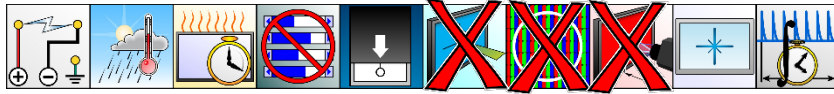
Fig. 1. Design eye position and interpupillary distance.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example (cd m^{-2})	
L_{LWW}	169.3
L_{RWW}	156.4
—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example (cd m^{-2})	
L_{ave}	162.8

17.3.4 TWO-VIEW AUTOSTEREOSCOPIC LUMINANCE UNIFORMITY

DESCRIPTION: Measure the stereoscopic luminance uniformity of a two-view autostereoscopic display at nine specified points on display panel.

Unit: %. Symbols: $\mathcal{U}_L, \mathcal{U}_R$.



SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. Measure at nine locations at the centers of a 3×3 matrix covering the screen—see Fig. 1. Test patterns to be used are two-view white/white images designated left eye/right eye.

PROCEDURE: The designated eye position (DEP) is z_{DEP} . The interpupillary distance (IPD) is Δx_{IPD} . For displays with eye-tracking that function must be disabled

1. Place the LMD at the position of left eye: $x = -\Delta x_{\text{IPD}}/2$, $y = 0$, $z = z_{\text{DEP}}$. The center of the front of the lens of the LMD must be rotated about this point to view all nine positions so that this left-eye point remains fixed in space.
2. Measure the luminance $L_{LWW}(i)$ the white/white pattern for the nine locations on the screen $i = 1, 2, \dots, 9$.
3. Place the LMD at the position of right eye: $x = +\Delta x_{\text{IPD}}/2$, $y = 0$, $z = z_{\text{DEP}}$. The center of the front of the lens of the LMD must be rotated about this point to view all nine positions so that this left-eye point remains fixed in space.
4. Measure the luminance $L_{RWW}(i)$ the white/white pattern for the nine locations on the screen $i = 1, 2, \dots, 9$.

ANALYSIS: We determine the minimum luminance and the maximum luminance for the left and right eyes and calculate the stereoscopic luminance uniformity \mathcal{U}_L , \mathcal{U}_R for each eye for a two-view-display:

$$u_l = \frac{\min[L_{LWW}(i)]}{\max[L_{LWW}(j)]}, i, j = 1, 2, \dots, 9 \quad (1)$$

$$\mathcal{U}_R = \frac{\min[L_{RW}(i)]}{\max[L_{RW}(j)]}, i, j = 1, 2, \dots, 9 \quad (2)$$

Here, the min and max functions establish the minimum and maximum values of any set of measurements.

REPORTING: The 3D luminance uniformity values \mathcal{U}_L , \mathcal{U}_R for the left and right eyes respectively are reported either as a number or percentage to no more than three significant figures.

COMMENTS: Light leakage between the channels is included in these measurements. In addition, these measurements are made at designated eye positions to the nine specified points of a display to evaluate the luminance from different positions arriving at the viewer's eyes. Therefore, the measurement method of stereoscopic luminance uniformity is different from that of conventional 2D luminance uniformity where all the measurements can be made from the normal direction.

1	2	3
4	5	6
7	8	9

Fig. 1. Location of measurement points. Location #5 is the center of the screen.

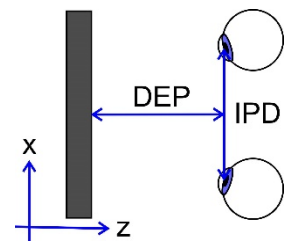


Fig. 2. Design eye position and inter-pupillary distance.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Analysis example (cd m ⁻²)		
Locations	L_{LWW}	L_{RWW}
1	153.0	151.3
2	151.2	151.3
3	147.8	150.3
4	156.1	154.2
5	169.3	156.4
6	157.4	155.6
7	146.3	146.6
8	131.5	131.0
9	141.4	142.6
Minimum:	131.5	131.0
Maximum:	169.3	156.4

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example	
u_L	77.6 %
u_R	83.7 %



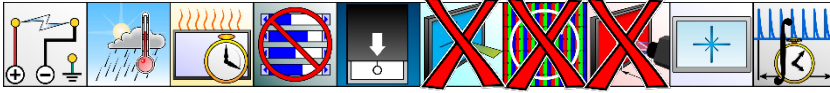
17.3.5 TWO-VIEW AUTOSTEREOSCOPIC ANGULAR RANGE

ALIAS: autostereoscopic horizontal viewing angle

DESCRIPTION: Measure the stereoscopic system crosstalk profiles as a function of horizontal viewing angle of a two-view autostereoscopic display at the display center. We will use these profiles to determine the angular range within which the system crosstalk exceeds selected threshold.

Unit: degree. **Symbols:** $X_L(\theta)$, $X_R(\theta)$, θ_L , θ_R .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. The LMD is centered on the screen normal at a radius r_{DEP} of the design eye point. The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ (preferably 0.2°). Test patterns to be used are two-view images designated left eye/right eye: (a) black/black, (b) black/white, and (c) white/black.

PROCEDURE: Measure the angular luminance profiles at the radius r_{DEP} of the design eye position for the following left/right images (a) black/black, (b) black/white, and (c) white/black. The resulting luminance profiles are $L_{\text{KK}}(\theta)$, $L_{\text{KW}}(\theta)$, and $L_{\text{WK}}(\theta)$ — see Fig. 2. The range of horizontal angles to use should be specified by the manufacturer (the useful angular range for the DUT, e.g., $-\theta_h$ to $+\theta_h$). In the following procedure, we will start at the normal position ($\theta = 0$) and rotate in either direction. For displays with eye-tracking the function must be disabled.

1. Place the LMD at the center position: $x = 0$, $y = 0$, $z = z_{\text{DEP}}$.
2. Measure the required luminances $L_{\text{KK}}(0)$, $L_{\text{KW}}(0)$, and $L_{\text{WK}}(0)$:
3. Over a specified range of angles $-\theta_h$ to $+\theta_h$ at an angular step of $\Delta\theta \leq 0.5^\circ$ (preferably 0.2°) repeat this process maintaining the radius of LMD at r_{DEP} .

ANALYSIS: The luminance profiles are used to calculate the crosstalk profiles (see Fig. 3):

1. Calculate stereoscopic system crosstalk profile $X_L(\theta)$ and $X_R(\theta)$ for the left and right eye respectively from the values of angular luminance profiles $L_{\text{KK}}(\theta)$, $L_{\text{KW}}(\theta)$, and $L_{\text{WK}}(\theta)$ shown in Fig. 2. These can be reported as numbers or as percentages.

$$X_L(\theta) = \frac{L_{\text{KW}}(\theta) - L_{\text{KK}}(\theta)}{L_{\text{WK}}(\theta) - L_{\text{KK}}(\theta)}, \quad (1)$$

$$X_R(\theta) = \frac{L_{\text{WK}}(\theta) - L_{\text{KK}}(\theta)}{L_{\text{KW}}(\theta) - L_{\text{KK}}(\theta)}. \quad (2)$$

2. From equations (1) and (2), the profiles of system cross talks vs. angle, $X_L(\theta)$ and $X_R(\theta)$, can be plotted for each eye using the valleys of the profiles as shown in Fig. 3.
3. **Using thresholds:** The stereoscopic angular range depends on the viewer's acceptance of the stereoscopic system crosstalk. After an acceptable value of stereoscopic system crosstalk X_{th} is decided upon by all interested parties, the angles θ_L and θ_R are determined based upon the maximum angular range where the crosstalk profiles minima are lower than the system crosstalk threshold value.
4. The angle θ_L is determined by the included angle of the outmost two $X_L(\theta)$ valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for left eye; θ_R is determined by the included angle of the outmost $X_R(\theta)$ two valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for right eye.

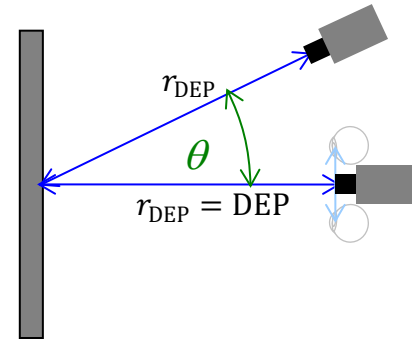


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Analysis example:	
$X_L(-49.6^\circ)$	6.7%
$X_R(-46.4^\circ)$	6.4%
...	
$X_L(-29.8^\circ)$	4.2%
$X_L(-23.4^\circ)$	3.4%
...	
$X_L(18.8^\circ)$	3.4%
$X_R(22.4^\circ)$	3.4%
$X_L(29.2^\circ)$	3.7%
:	



REPORTING: Report the graphs of the crosstalk profiles. If a threshold X_{th} has been selected, then report angles θ_L and θ_R for the left and right eyes such that the crosstalk is equal to or below that threshold—see Fig. 3.

COMMENTS: Although the description presented here is for two-view autostereoscopic displays, the method can be used for multi-view autostereoscopic displays; L and R then correspond to odd and even view numbers, as described in the following main section.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
L_{ave}	162.8
θ_L	42.2°
θ_R	49.2°
X_{th}	3.6%

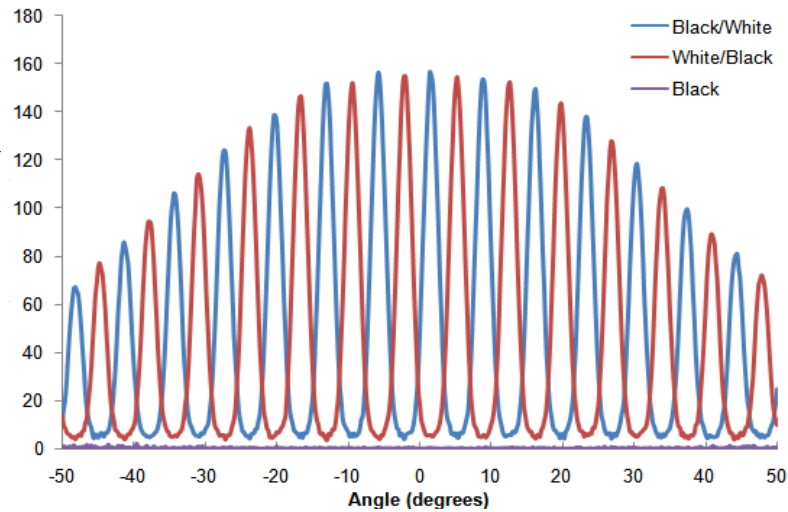


Fig. 2. Example of luminance distribution for patterns $L_{WK}(\theta)$ (red curve as would be seen with the left eye), $L_{KW}(\theta)$ (blue curve as would be seen with the right eye), and $L_{KK}(\theta)$ the background black level.

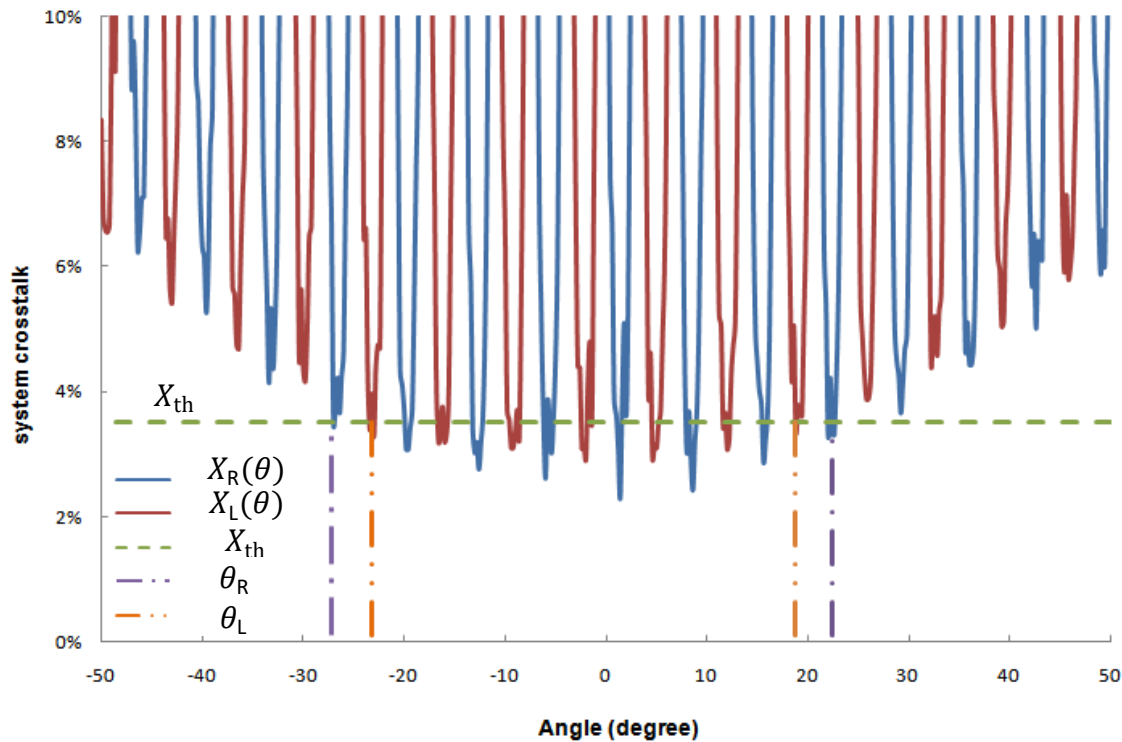


Fig. 3. Example of distribution of system crosstalk vs. angle.

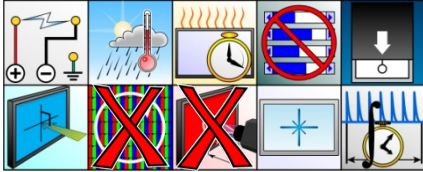


17.3.6 TWO-VIEW AUTOSTEREOSCOPIC OPTIMUM VIEWING DISTANCE

DESCRIPTION: Determine the distance of a two-view autostereoscopic display from which the 3D image is best viewed. **Unit:** mm. **Symbols:** Z_{OVD} .

When the viewer eye is at the optimum viewing distance (OVD) then the viewer will see lowest crosstalk from both points 4 and 6 of the screen in Fig. 1. Using the angles of the minimum crosstalk for points 4 and 6 for one eye (θ_{P4} , and θ_{P6}) we can calculate the optimal distance. Figure 2 is showing the geometrical relations.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is in excess of that specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ but preferably 0.2° . Test patterns are for each of the views: all views black and an image where one view is white and other views are black. For displays with eye-tracking the function must be disabled.

PROCEDURE & ANALYSIS:

- 1 Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
- 2 Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views' images black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]
- 3 Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \dots, n$ for each view i and determine the angles of crosstalk minima θ_i , $i = 1, 2, \dots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk.
- 4 Repeat the stereoscopic crosstalk measurement for the same view from a different display location (note: points must be in same display row, for example, choose points 4 and 6 from the 9-point uniformity chart).
- 5 Determine from stereoscopic crosstalk profiles the angles θ_i , at which the minima occur.
- 6 Measure the distance D between the two screen locations. These are the locations where the images are optimally separated ("sweet spots").
- 7 Optimum viewing distance can be determined by investigating measurement results from the crosstalk minima angles of the measured view. Following equation assumes that points 4 and 6 from the 9-point uniformity chart are used:

$$Z_{OVD} = \frac{D}{\tan \theta_{P4} + \tan \theta_{P6}} \quad (1)$$

REPORTING: Report the optimum viewing distance value Z_{OVD} in mm.

COMMENTS: None.

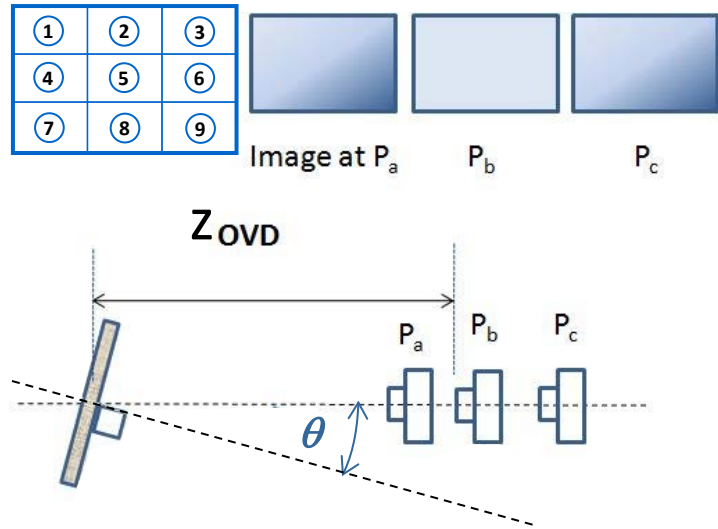


Fig. 1. Effects of different viewing distances and the optimum viewing distance. Measurement locations at the upper left.

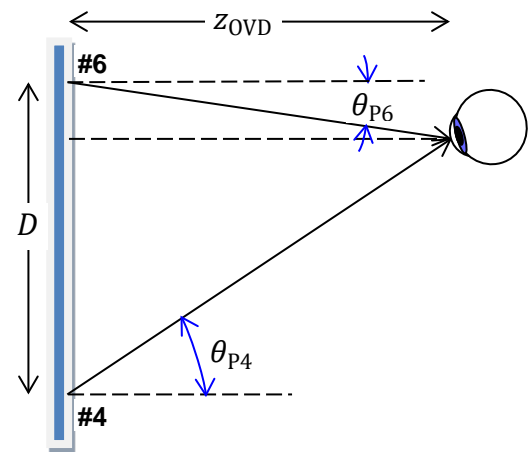


Fig. 2. Geometrical relations of the optimal viewing distance (shown for left eye).

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
Z_{OVD}	600 mm



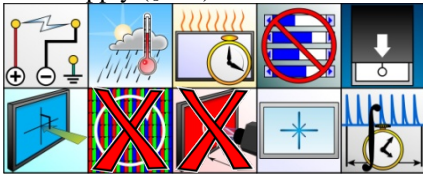
17.3.7 TWO-VIEW AUTOSTEREOSCOPIC VIEWING RANGE

DESCRIPTION: Determine the usable horizontal viewing range of a two-view autostereoscopic display (for tracked or non-tracked displays). The range is determined by the minimum (or usable limit) extinction ratio as a function of angle.

Unit: mm. **Symbols:** Z_{OVR} .

When the viewer's eyes are within the optimum viewing range (OVR) then the viewer will see the lowest crosstalk from both points 4 and 6 of the 9 points shown in Fig. 1. Using the angles of the minimal crosstalk for points 4 and 6 for one eye (θ_{P4} , and θ_{P6}) we can calculate the optimal distance. Figure 2 shows the geometric relations.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\leq 0.25^\circ$ and preferably $\leq 0.2^\circ$. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. (This range is greater than the range specified by the manufacturer by one lobe of optimal view.) The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ but preferably 0.2° . Test patterns are for each of the views: all views black and an image where one view is white and other views are black. For displays with eye-tracking the function must be disabled.

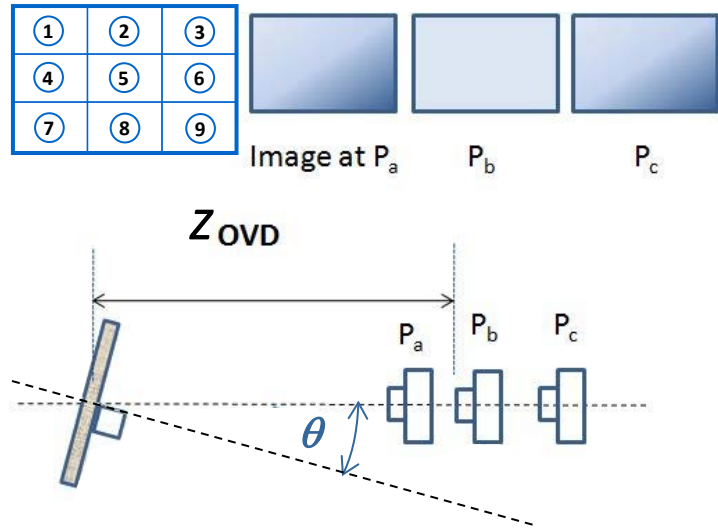


Fig. 1. Effects of different viewing distances and the optimum viewing distance. Measurement locations at the upper left.

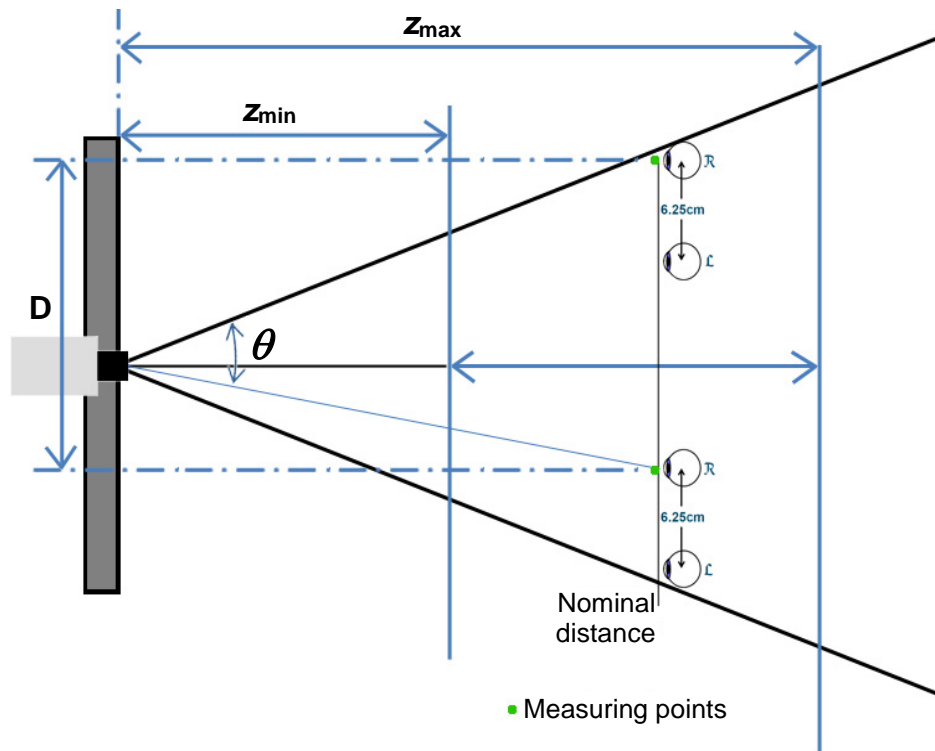


Fig. 2. Geometrical relations of the optimal viewing range

**PROCEDURE & ANALYSIS:**

- 1 Measure the luminance profile $L_K(\theta)$ of the display when all the views are black. See Fig. 3.
- 2 Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views image black. The summary of the individual view luminance should look approximately the same as the stereoscopic luminance profile measured when all the views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]
- 3 Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \dots, n$ for each view i and determine the angles of crosstalk minima θ_i , $i = 1, 2, \dots, n$. See Eq. (2) of 17.4.1 Two-view Autostereoscopic Crosstalk.
- 4 Repeat the stereoscopic crosstalk measurement for the same view from a different display location (note: points must be in same display row, for example, choose points 4 and 6 from the 9-point uniformity chart, and additional points 2 and 8).
- 5 Determine from stereoscopic crosstalk profiles the angles θ_i , at which the minima occur.
- 6 Measure the distance D between the two screen locations. These are the locations where the images are optimally separated (“sweet spots”).
- 7 Optimum viewing distance can be determined by investigating measurement results from the crosstalk minima angles of the measured view. Following equation assumes that points 4 and 6 from the 9-point uniformity chart are used:

$$Z_{OVR} = Z_{\max} - Z_{\min} \quad (1)$$

$$Z_{\max} = \frac{D_{\min}}{\tan \theta_{P4} + \tan \theta_{P6}} \quad (2)$$

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
Z_{OVR}	600 mm

REPORTING: Report the optimum viewing distance value Z_{OVR} in mm.

COMMENTS: We normally check the range with the center points 4 and 6, but we could also do it for any other horizontal pair of Fig. 1, such as points 1 and 3 or points 7 and 9.

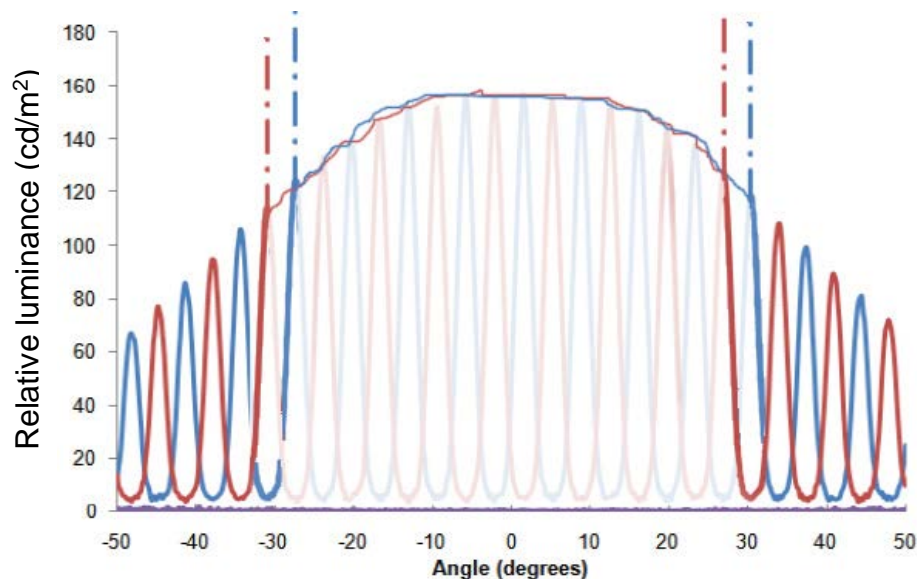


Fig. 3. Example of luminance distribution for patterns $L_{WK}(\theta)$ (red curve as would be seen with the left eye), $L_{KW}(\theta)$ (blue curve as would be seen with the right eye), and $L_{KK}(\theta)$ the background black level.



17.4 AUTOSTEREOSCOPIC DISPLAYS WITH MULTIPLE VIEWS

This main section deals with stereoscopic displays, without the use of any glasses, in which the viewer can be positioned in multiple locations with clearly defined separate views. We will refer to this type of stereoscopic display as multi-view autostereoscopic displays. For a comparison with two-view autostereoscopic displays, see the introduction in 17.3. The following measurement methods are covered in this chapter:

1. Multiview autostereoscopic crosstalk
2. Multiview autostereoscopic luminance
3. Multiview autostereoscopic luminance uniformity
4. Multiview autostereoscopic contrast ratio
5. Multiview autostereoscopic optimum viewing distance
6. Multiview autostereoscopic angular range
7. Multiview angular resolution
8. Multiview valid viewing area
9. Multiview 3D geometry distortion
10. Multiview spatial blur edge width ratio

Many of the measurement methods contained in the rest of this document are also applicable to 3D displays and can be adapted accordingly.

The measurements in this section include angular scanning in small angular increments to find the optimal viewing locations, *i.e.* angles of minimum crosstalk (“sweet spots”), and the angular dependence in their vicinity. The scanning can be done with a spot photometer (LMD) mounted on a rotating stage (goniometric setup), a fixed LMD with the display rotating around the center vertical axis in the image plane, or with a high-resolution conoscopic camera. In case of an LMD, the focal distance should match the viewing distance. Because of the sensitivity to the measurement-field angle θ_{MFA} , we recommend $\theta_{MFA} \leq 0.25^\circ$, preferably $\theta_{MFA} \leq 0.2^\circ$. When using a conoscopic camera, the measurement distance should equal the working distance of the camera.

Figure 1 shows an example of a multi-view autostereoscopic display with five views. In the two-view case, it is possible to use red-blue notation for both the luminance and crosstalk curves because there are only right and left eye views. In the multi-view case, however, every view can be considered to be either a left or a right eye view, depending on the user location with respect to the display. A stereoscopic image is perceived when the view number of the right eye is larger than that of the left eye. For instance, the location where the left eye sees view #1 and the right eye sees view #4 results in a stereoscopic image. On the other hand, a location where the left eye sees view #4 and the right eye sees view #2 results in pseudo-stereo. Displays with a large number of views enable stereoscopic image perception for several combinations of display views so it is not possible to assign each display view to either right eye or left eye view.

An angular scan of one view at full white will reveal the luminance distribution near the optimum angles (“sweet spots”), which is low until the occurrence of the next view with the same number (see Fig. 1). When the luminance in one view is maximum all other views have a low luminance, but not zero, so all views will therefore contribute to the crosstalk. A typical scan of a seven-view multi-view display is shown in Fig. 2, where each separate scan is shown in different colors (01w, 02w, ..., 07w). The scan with views at full white and black is labeled W and K, respectively.

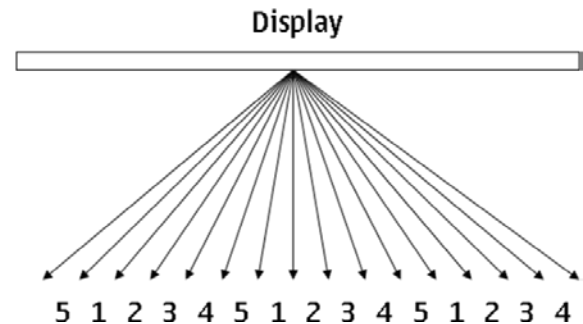


Fig. 1. Multiview autostereoscopic five views display with optimal view directions labeled and the repetition behavior.

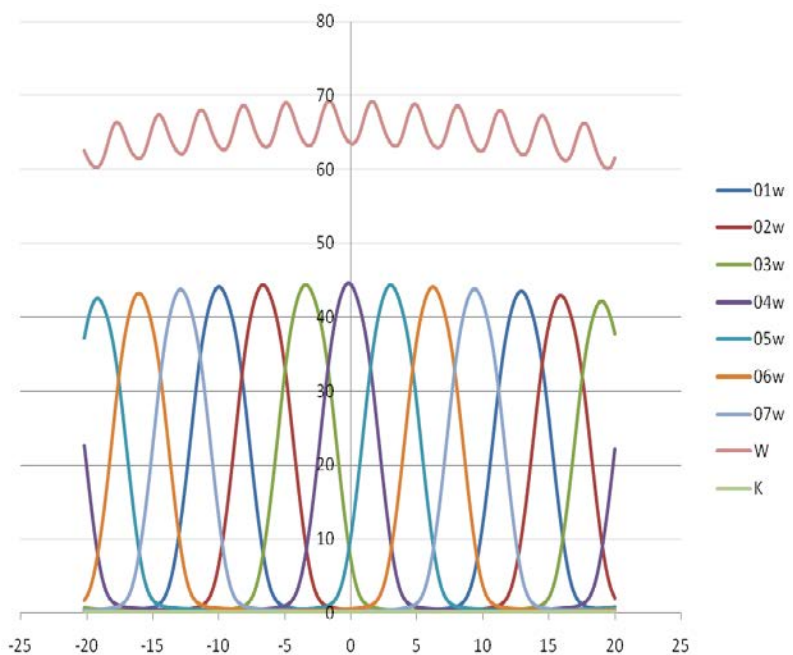


Fig. 2. Example of scans of a seven-view multi-view parallax-barrier autostereoscopic display. The abscissa is in angles from the normal and the ordinate is luminance in cd m^{-2} .

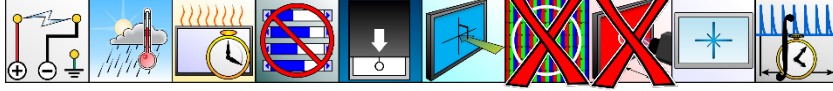


17.4.1 MULTIVIEW AUTOSTEREOSCOPIC CROSSTALK

ALIAS: ghost image, 3D crosstalk, 3D extinction ratio

DESCRIPTION: We measure the stereoscopic crosstalk and extinction ratio of a multi-view autostereoscopic display. **Unit:** %. **Symbols:** X_{MVave}

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the screen center maintaining the radius r_{DEP} and pointing at the screen center. This range should be in excess of that specified by the manufacturer by one lobe of optimal view. The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ but preferably $\Delta\theta \leq 0.2^\circ$. Test patterns are for each of the views: all views white, all views black, and an image where one view is white and other views are black.

PROCEDURE: Consider a multi-view autostereoscopic display with n views. Measure the angular luminance profiles at the radius r_{DEP} of the design eye position over the specified range of horizontal angles for the following:

1. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
2. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
3. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$, with the view image i white and the other views' images black. The sum of the individual view luminance profiles should be approximately equal to the stereoscopic luminance profile measured when all views are white,

$$L_W(\theta) \cong \sum_{i=1}^n L_i(\theta). \quad (1)$$

ANALYSIS: Calculate overall stereoscopic crosstalk $X_i(\theta)$, $i = 1, 2, \dots, n$, for each view i : For each individual view $L_i(\theta)$ we subtract off the black profile $L_K(\theta)$, then sum up those views (index j), which would be a little smaller than $L_W(\theta)$ because of the black subtraction. The sum of views is in curly brackets in Eq. (2). We then subtract the net luminance profile of view i , $[L_i(\theta) - L_K(\theta)]$, from that sum to obtain a quantity that characterizes all the light from the other views (the numerator) that spills into view i . Then we divide by the net luminance profile of view i .

$$X_i(\theta) = \frac{\left\{ \sum_{j=1}^n [L_j(\theta) - L_K(\theta)] \right\} - [L_i(\theta) - L_K(\theta)]}{L_i(\theta) - L_K(\theta)} = \frac{\sum_{j=1}^n [L_j(\theta) - L_K(\theta)]}{L_i(\theta) - L_K(\theta)} - 1 \quad (2)$$

From the resulting stereoscopic crosstalk curves find the angles for the local minima θ_j . Calculate the average crosstalk:

$$X_{MVave} = \frac{1}{n} \sum_{j=1}^n X_j(\theta_j) \quad (3)$$

REPORTING: Report the crosstalk average value X_{MVave} as a number or in percent.

COMMENTS: None.

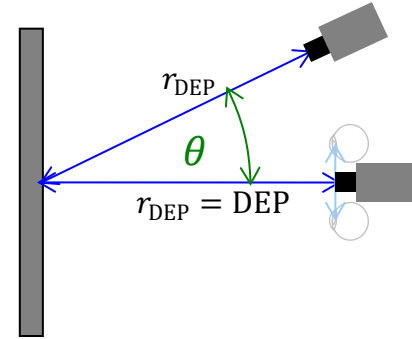


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Analysis example:

X_1	63 %
X_2	61 %
...	
X_n	45 %

—SAMPLE DATA ONLY—
Do not use any values shown to represent expected results of your measurements.

Reporting example

Center	X_{MVave}	62 %
--------	-------------	------

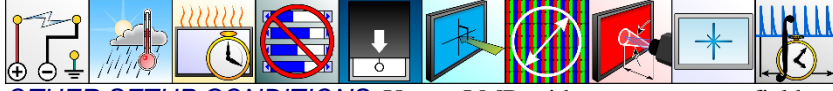


17.4.2 MULTIVIEW AUTOSTEREOSCOPIC LUMINANCE

DESCRIPTION: Measure the average stereoscopic luminance of a multi-view autostereoscopic display. **Unit:** cd m^{-2} . **Symbol:** L_{MVave} .

We measure the luminance profile (luminance as a function of angle) over an appropriate range of angles in excess of the range specified by the manufacturer (in excess by one lobe of optimum view or “sweet spot”). We examine the crosstalk profiles and determine the angles for which the crosstalk is a minimum. Then we average the luminances at those angles.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle $\theta_{\text{MFA}} \leq 0.25^\circ$ and preferably $\theta_{\text{MFA}} \leq 0.2^\circ$. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. This range is in excess of that specified by the manufacturer by one lobe of optimal view. The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ but preferably $\Delta\theta \leq 0.2^\circ$. Test patterns are for each of the views: all views white, all views black, and an image where one view is white and other views are black.

PROCEDURE: Consider a multi-view autostereoscopic display with n views. Measure the angular luminance profiles at the radius r_{DEP} of the design eye position over the specified range of horizontal angles for the following:

1. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
2. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
3. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views' images black. The sum of the individual view luminance profiles should be approximately equal to the stereoscopic luminance profile measured when all views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk].

ANALYSIS: Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \dots, n$ for each view i and determine the angles of crosstalk minima θ_i , $i = 1, 2, \dots, n$. See Eq. (2) of 17.4.1 (multi-view autostereoscopic crosstalk). Calculate the average luminance of over those angles:

$$L_{\text{MVave}} = \frac{1}{n} \sum_{i=1}^n L_W(\theta_i) \quad (1)$$

REPORTING: The reported average luminance value L_{MVave}

COMMENTS: None.

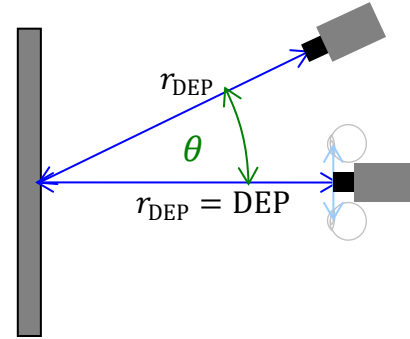


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Analysis example:	
L_1	220
L_2	212
...	
L_n	158

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting example (cd m^{-2})		
Center	L_{MVave}	192



17.4.3 MULTIVIEW AUTOSTEREOSCOPIC LUMINANCE UNIFORMITY

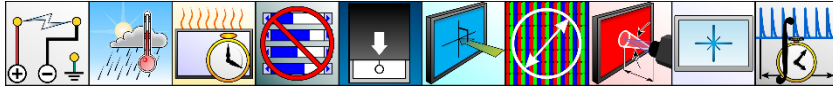
ALIAS: Banding, 3D moiré

DESCRIPTION: Determine the stereoscopic luminance uniformity of a multi-view autostereoscopic display (determining the magnitude of a flicker type of variation in the luminance, when the DUT is rotated).

Unit: %. **Symbol:** \mathcal{U}_{MV3D} .

We measure the luminance profile (luminance as a function of angle) over an appropriate range of angles in excess of the range specified by the manufacturer (in excess by one lobe of optimal view or “sweet spot”). The ratio between the minimum luminance and the maximum luminance over that range of angles is the stereoscopic luminance uniformity.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. This range is in excess of that specified by the manufacturer by one lobe of optimal view. The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ but preferably $\Delta\theta \leq 0.2^\circ$. Test patterns are for each of the views: all views white, all views black, and an image where one view is white and other views are black.

PROCEDURE: Consider a multi-view autostereoscopic display with n views. Measure the angular luminance profiles at the radius r_{DEP} of the design eye point and over the specified range of horizontal angles for the following:

1. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
2. Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
3. Measure the luminance profiles for individual views $L_{W_i}(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views' images black. The sum of the individual view luminance profiles should be approximately equal to the stereoscopic luminance profile measured when all views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk].

ANALYSIS: Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \dots, n$ for each view i and determine the angles of crosstalk minima θ_i , $i = 1, 2, \dots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk. Between the angles θ_i determine the angles of the luminance minima θ_j —see Fig. 2. The uniformity of the stereoscopic luminance for a multi-view autostereoscopic display is:

$$\mathcal{U}_{MV3D} = \frac{\max L_W(\theta_i) - \min L_W(\theta_j)}{\max L_W(\theta_i)} \quad (1)$$

REPORTING: Report the stereoscopic luminance uniformity value \mathcal{U}_{MV3D} as a number or in percent.

COMMENTS: Expert evaluation may be a practical solution for the evaluation of the existence of 3D Moiré.

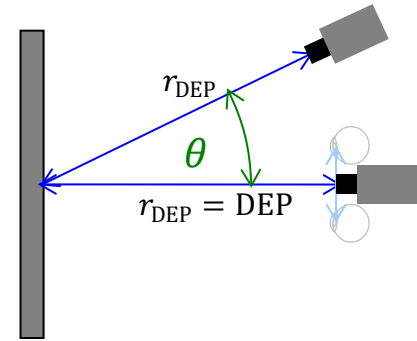


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

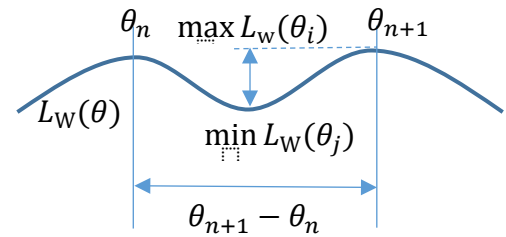


Fig. 2. Luminance variation from an angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting example		
Center	\mathcal{U}_{MV3D}	80%



17.4.4 MULTIVIEW AUTOSTEREOSCOPIC CONTRAST RATIO

DESCRIPTION: Determine the stereoscopic contrast ratio of a multi-view autostereoscopic display. Stereoscopic contrast ratio is measured from the crosstalk minima angles θ_i similarly to the stereoscopic luminance. If both crosstalk and luminance are already measured, the following calculation is all that is needed; C_{MV3D} is the average of all the $C_{MV3D}(\theta_i)$ values.

Units: none, **Symbols:** C_{MV3D} .

SETUP & PROCEDURE: None, use the same data from § 17.4.3 Multiview Autostereoscopic Luminance.

ANALYSIS: Calculate the stereoscopic contrast ratio $C_{MV3D}(\theta_i)$ for each of the optimal viewing angles $\theta_i, i = 1, 2, \dots, n$:

$$C_{MV3D}(\theta_i) = \frac{L_W(\theta_i)}{L_K(\theta_i)} \quad (1)$$

The crosstalk between one view is compared to the neighbor view, which is supposed to be black. Therefore, we should note that for a specific angle the full white is compared to the neighbor view, which is black. The average of the above is the stereoscopic contrast ratio:

$$C_{MV3D} = \frac{1}{n} \sum_{i=1}^n \frac{L_W(\theta_i)}{L_K(\theta_i)}. \quad (2)$$

REPORTING: Report the final C_{MV3D} value.

COMMENTS: None.

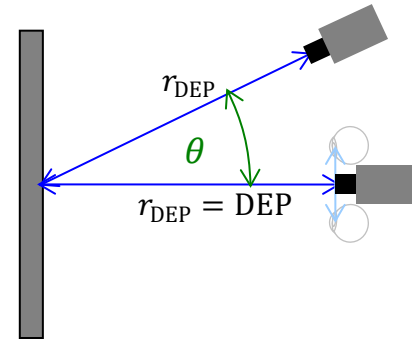


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.		
Reporting example		
Center	C_{MV3D}	250



AVOID DIAGNOSTICS

**It's easier to deal
with ignorance!**

(Ostriches don't really do this;
it is a legend called the "ostrich effect.")

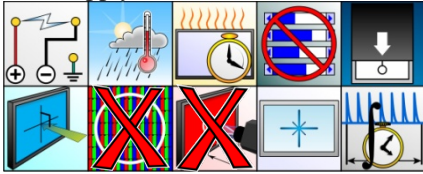


17.4.5 MULTI-VIEW AUTOSTEREOSCOPIC OPTIMUM VIEWING DISTANCE

DESCRIPTION: Determine the distance of a multi-view autostereoscopic display from which the 3D image is best viewed. **Unit:** mm. **Symbol:** Z_{OVD} .

When the viewer eye is in the optimum viewing distance (OVD) then the viewer will see lowest crosstalk from both points 4 and 6 of the screen in Fig. 1. Using the angles of the minimal crosstalk for points 4 and 6 for one eye (θ_{P4} and θ_{P6}) we can calculate the optimal distance. Fig. 2 shows the geometrical relations.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is rotated over the range of horizontal angles $-\theta_h$ to $+\theta_h$ about the center screen maintaining the radius r_{DEP} and pointing at the screen center. This range is in excess of that specified by the manufacturer by one lobe of optimal view. The LMD is positioned using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ but preferably $\Delta\theta \leq 0.2^\circ$. Test patterns are for each of the views: all views black and an image where one view is white and other views are black.

PROCEDURE & ANALYSIS:

- 1 Measure the luminance profile $L_K(\theta)$ of the display when all the views are black.
- 2 Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views' images black. The sum of the individual view luminance profiles should be approximately equal to the stereoscopic luminance profile measured when all views are white [c.f. Eq. (1) of 17.4.1 Multiview Autostereoscopic Crosstalk]
- 3 Calculate the stereoscopic crosstalk profile $X_i(\theta)$, $i = 1, 2, \dots, n$ for each view i and determine the angles of crosstalk minima θ_i , $i = 1, 2, \dots, n$. See Eq. (2) of 17.4.1 Multiview Autostereoscopic Crosstalk.
- 4 Repeat the stereoscopic crosstalk measurement for the same view from a different display location (note: points must be in same display row, for example, choose points 4 and 6 from the 9-point uniformity chart).
- 5 Determine from stereoscopic crosstalk profiles the angles θ_i , at which the minima occur.
- 6 Measure the distance D between the two screen locations or calculate it from the display specifications (pixel count, pixel pitch/display size). These are the locations where the images are optimally separated ("sweet spots").
- 7 Optimum viewing distance can be determined by investigating measurement results from the crosstalk minima angles of the measured views. The following equation assumes that points 4 and 6 from the 9-point uniformity chart are used:

$$Z_{OVD} = \frac{D}{\tan \theta_{P4} + \tan \theta_{P6}}$$

REPORTING: Report the optimum viewing distance value Z_{OVD} in mm.

COMMENTS: None.

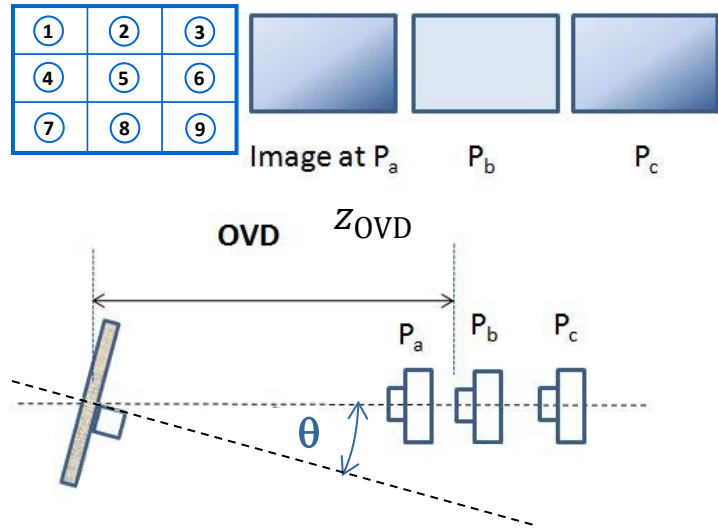


Fig. 1. Effects of different viewing distances and the optimum viewing distance. Measurement locations at the upper left.

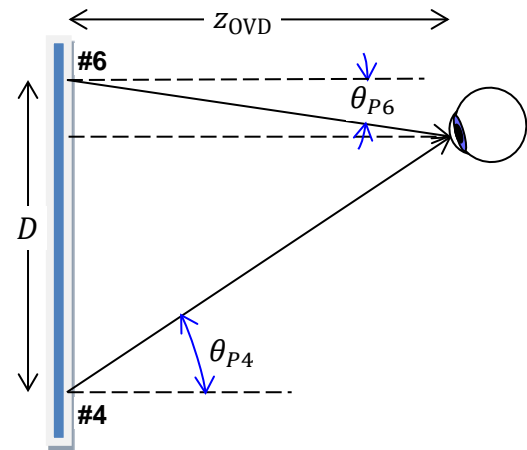


Fig. 2. Geometrical relations of the optimal viewing distance (shown for left eye).

(1)

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
Z_{OVD}	600 mm

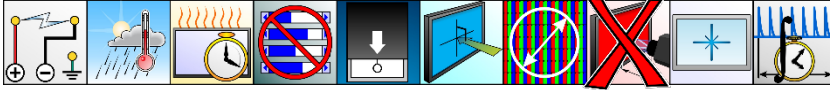


17.4.6 MULTIVIEW AUTOSTEREOSCOPIC ANGULAR RANGE

ALIAS: autostereoscopic horizontal viewing angle

DESCRIPTION: Measure the stereoscopic system crosstalk profiles at the center as a function of horizontal viewing angle of two views of a multi-view autostereoscopic display, so that left eye is viewing the left image and the right eye is viewing the right image of a pair. We will use these profiles to determine the angular range within which the system crosstalk exceeds the selected threshold. **Unit:** degree. **Symbols:** $X_L(\theta)$, $X_R(\theta)$, θ_L , θ_R .

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is centered on the screen normal at a radius r_{DEP} of the design eye position.

The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ (preferably $\Delta\theta \leq 0.2^\circ$). Test patterns to be used are two-view images designated left/right eye: (a) black/black, (b) black/white, and (c) white/black. Note that the two views are not necessarily the physically adjacent ones.

PROCEDURE: Measure the angular luminance profiles at the radius r_{DEP} of the design eye position for the following left/right images (a) black/black, (b) black/white, and (c) white/black. The resulting luminance profiles are $L_{kk}(\theta)$, $L_{KW}(\theta)$, and $L_{WK}(\theta)$ —see Fig. 2. The range of horizontal angles to use should be specified by the manufacturer (the useful angular range of the DUT, e.g., $-\theta_h$ to $+\theta_h$). In the following procedure, we will start at the normal position ($\theta = 0$) and rotate in either direction.

1. Place the LMD at the center position: $x = 0, y = 0, z = z_{DEP}$.
2. Measure the required luminances $L_{KK}(0)$, $L_{KW}(0)$, and $L_{WK}(0)$
3. Over a specified range of angles $-\theta_h$ to $+\theta_h$ at angular steps of $\Delta\theta \leq 0.5^\circ$ (preferably 0.2°) repeat this process maintaining the radius of LMD at r_{DEP} .

ANALYSIS: The luminance profiles are used to calculate the crosstalk profiles (see Fig. 3):

1. Calculate stereoscopic system crosstalk profile $X_L(\theta)$ and $X_R(\theta)$ for the left and right eye, respectively, from the values of angular luminance profiles $L_{KK}(\theta)$, $L_{KW}(\theta)$, and $L_{WK}(\theta)$ shown in Fig. 2.

$$X_L(\theta) = \frac{L_{KW}(\theta) - L_{KK}(\theta)}{L_{WK}(\theta) - L_{KK}(\theta)}, \quad (1)$$

$$X_R(\theta) = \frac{L_{WK}(\theta) - L_{KK}(\theta)}{L_{KW}(\theta) - L_{KK}(\theta)}. \quad (2)$$

2. From equations (1) and (2), the profiles of system cross talks vs. angle, $X_L(\theta)$ and $X_R(\theta)$, can be plotted for each eye using the valleys of the profiles as shown in Fig. 3.
3. **Using thresholds:** The stereoscopic angular range depends on the viewer's acceptance of the stereoscopic system crosstalk. After an acceptable value of stereoscopic system crosstalk X_{th} is decided upon by all interested parties, the angles θ_L and θ_R are determined based upon the maximum angular range where the crosstalk profiles minima are lower than the threshold value.
4. The angle θ_L is determined by the included angle of the outmost two $X_L(\theta)$ valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for left eye; θ_R is determined by the included angle of the outmost $X_R(\theta)$ two valleys intersected by the threshold value X_{th} of the stereoscopic system crosstalk for right eye. These can be tabulated as numbers or percentages.

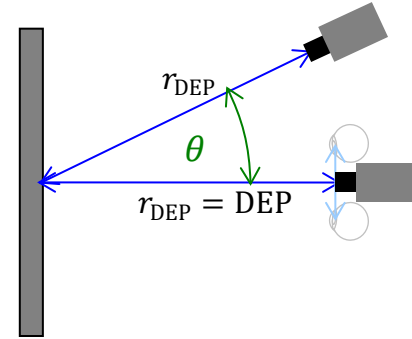


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example:	
$X_L(-49.6^\circ)$	6.7%
$X_R(-46.4^\circ)$	6.4%
...	
$X_L(-29.8^\circ)$	4.2%
$X_R(-26.8^\circ)$	3.5%
$X_L(-23.4^\circ)$	3.4%
...	
$X_L(18.8^\circ)$	3.4%
$X_R(22.4^\circ)$	3.4%
$X_L(25.8^\circ)$	3.9%
$X_L(29.2^\circ)$	3.7%
:	



REPORTING: Report the graphs of the crosstalk profiles. If a threshold has been selected, then report the angles θ_L and θ_R for the left and right eyes such that the system crosstalk is equal to or less than that threshold—see Fig. 3.

COMMENTS: Although the description presented here is for two-views autostereoscopic displays, the method is applicable to multi-view autostereoscopic displays; L and R then correspond to odd and even view numbers, as will be described in a following main section.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

L_{ave}	162.8
θ_L	42.2°
θ_R	49.2°
X_c	3.6%

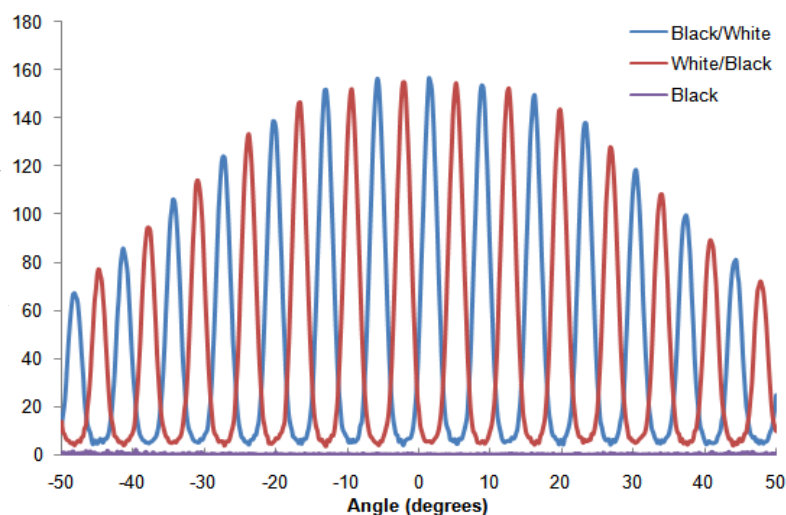


Fig. 2. Example of luminance distribution for patterns $L_{WK}(\theta)$ (red curve as would be seen with the left eye), $L_{KW}(\theta)$ (blue curve as would be seen with the right eye), and $L_{KK}(\theta)$ the background black level.

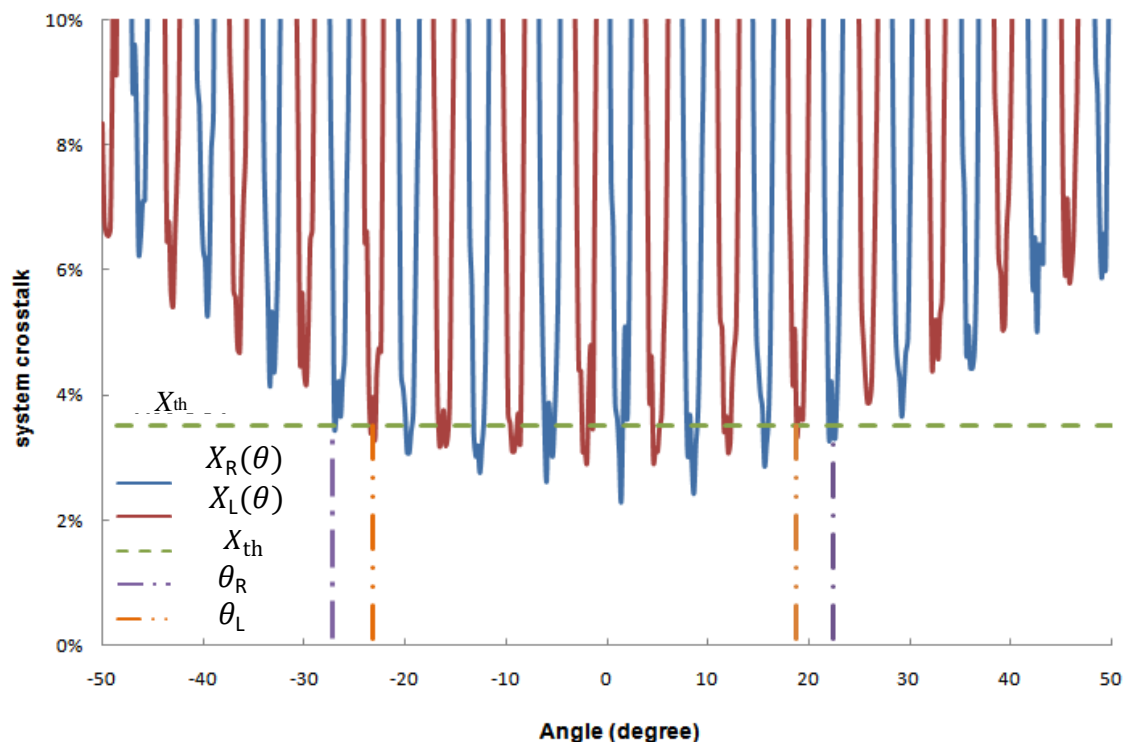
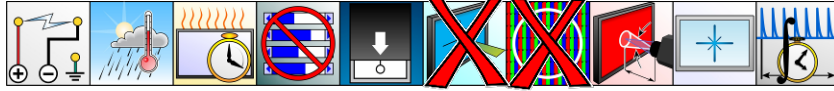


Fig. 3. Example of distribution of system crosstalk vs. angle.

17.4.7 MULTIVIEW ANGULAR RESOLUTION

ALIAS: depth range, depth of field

DESCRIPTION: Measure the angular resolution as a function of horizontal viewing angle of a multi-view display at the display center. We will use these profiles to determine the maximal displayable depth of field. **Units:** degree, meter. **Symbols:** $\Delta\theta$, d_F



APPLICATION: This measurement can also be applied to light-field autostereoscopic displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\theta_{\text{MFA}} \leq 0.25^\circ$ and preferably $\theta_{\text{MFA}} \leq 0.2^\circ$. The LMD is centered on the screen normal at a radius r_{DEP} of the design eye position (DEP). The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ (preferably $\Delta\theta \leq 0.2^\circ$). Test patterns to be used are two-view images designated left eye/right eye: (a) black/white, and (b) white/black.

PROCEDURE:

1. Measure the autostereoscopic angular range (17.3.5). Values are θ_L and θ_R for the left and right sides.
2. Measure the luminance profile of the display when all the views are white (L_W).
3. Measure the luminance profile of the display when all the views are black (L_K).
4. Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views' image black. The sum of the individual view luminance profiles should be approximately equal to the stereoscopic luminance profile measured when all views are white.

ANALYSIS:

1. Count the number of local maximum luminance values, N_{KW} , within the autostereoscopic viewing angular range as shown in Fig. 2 of 17.4.6 for the black/white test patterns.
2. Count the number of local maximum luminance values, N_{WK} , within the autostereoscopic viewing angular range as shown in Fig. 1 for the white/black test patterns.

REPORTING: The reported angular resolution value is $\Delta\theta$. The angular resolution $\Delta\theta$ is determined by dividing the sum of θ_L and θ_R by the number of periods between the local maxima:

$$\Delta\theta = \frac{\theta_L + \theta_R}{N_{WK} + N_{KW} - 1} \quad (1)$$

Maximal displayable depth of field, d_F , is closely related to the angular resolution. It can be calculated from the pixel size d_{pix} and the angular resolution $\Delta\theta$. d_F can be calculated by dividing the pixel size d_{pix} of the display by the tangent of the angular resolution:

$$d_F = \frac{d_{\text{pix}}}{\tan \Delta\theta} \quad (2)$$

COMMENT: Aliasing of the image (and/or other artifacts, depending on the type of the display) will occur.

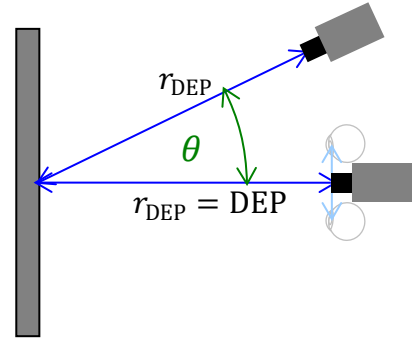


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Analysis example:	
$L_{KW}(-49.6^\circ)$	63
$L_{WK}(-46.4^\circ)$	75
:	
$L_{KW}(-29.8^\circ)$	120
$L_{WK}(-26.8^\circ)$	130
$L_{KW}(-23.4^\circ)$	138
:	
$L_{KW}(18.8^\circ)$	144
$L_{WK}(22.4^\circ)$	140
$L_{KW}(25.8^\circ)$	135
$L_{WK}(29.2^\circ)$	125
:	

<p>—SAMPLE DATA ONLY—</p> <p>Do not use any values shown to represent expected results of your measurements.</p>	
Reporting example	
$\Delta\theta$	1.3°
d_F	0.5m



17.4.8 VALID MULTIVIEW RANGE

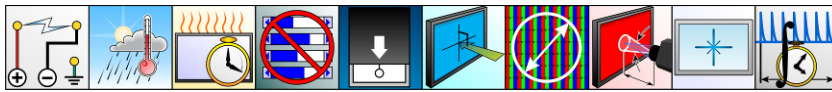
ALIAS: Field of view, viewing freedom

DESCRIPTION: Measure the field of view (FOV) and the valid multi-view range inside the FOV of a multi-view autostereoscopic display using quantitative and qualitative methods. The qualitative measurement method involves scanning in small angular increments to determine the valid viewing range, within which the display delivers the correct sign of the disparity between any pair of views. The scanning can be done either with a spot photometer LMD mounted on a moving stage capable of covering the presumable FOV range, or with a high-resolution conoscopic camera. Rotating the sample (the display) around the LMD is possible, but less practical.

Unit: percent (%). **Symbol:** V_{VA} .

APPLICATION: This measurement can also be applied to light-field autostereoscopic displays.

SETUP: As § 3.2).



LMD with a measurement field angle $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is centered on the screen normal at a radius r_{DEP} of the designated eye position, which should match the common area of the emitting zones in case of multi-view displays (optimal viewing distance). The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ (preferably $\Delta\theta \leq 0.2^\circ$).

This measurement requires two parallel LMDs separated by the standard Inter-Pupillary-Distance (IPD). For adults it is typically 6.25 cm (some use 6.5 cm.). Both LMDs are directed to the center of the screen. Since the LMDs are parallel, they will focus slightly left (-0.5 IPD) and slightly right (+0.5 IPD) from the display center. Alternatively, one LMD can be used in the two locations separated by the IPD (~6.5 cm). Measuring luminance profile will use a full white image test pattern.

In the case of discrete views, we need to identify the valid viewing area (the correct disparity). We should use steps of luminance pattern. In this case we use monochrome views, each with linear steps of luminance from 0 to 255. The value of luminance steps is calculated as 255 divided by the number of views. The luminance pattern should have 0 on the leftmost view and 255 on the rightmost side.

For the light-field, the method to identify valid viewing area (correct disparity) is: Use a test pattern with an angularly monotonic increasing grey-scale pattern (e.g. from 0 to 255). Scan the valid area of correct disparity. The border is at the first inflexion point of the intensity values measured in the scanning direction. The first pattern has 0 on the left side and 255 on the right side.

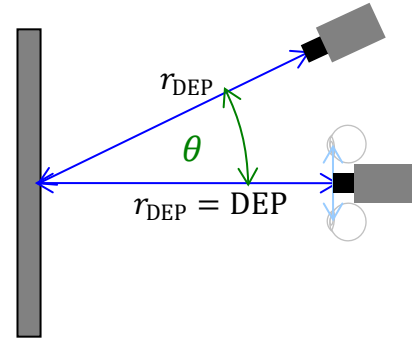


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

OTHER SETUP CONDITIONS: Use an

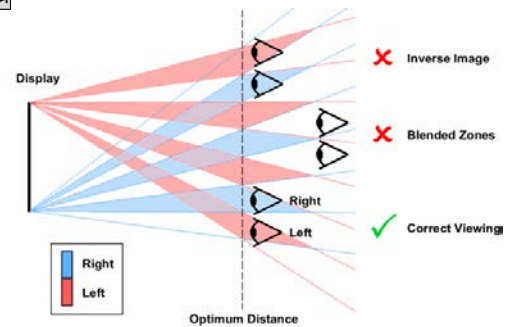


Fig.2. Example of zones having valid and invalid disparity.

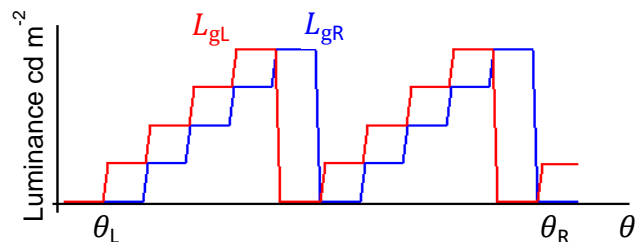


Fig.3. Example of measured grayscale profiles.

**PROCEDURE:**

Perform the following measurement steps to measure the viewing freedom:

1. Measure the autostereoscopic viewing angles θ_L and θ_R for the left and right sides. Further measurement steps must be done within the range of θ_L to θ_R .
2. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
3. Measure the left and right luminance profiles $L_{gL}(\theta)$ and $L_{gR}(\theta)$ of the display when the grayscale test pattern is displayed. A sample measurement is showed in Fig. 3.

ANALYSIS:

1. Normalize the measured grayscale luminance data by the full white luminance data.
2. Calculate luminance difference between the right and left detector data (see example graph in Fig. 4.):

$$L_{\text{diff}}(\theta) = \frac{L_{gR}(\theta) - L_{gL}(\theta)}{L_W(\theta)} \quad (1)$$

3. The resulting graph shows the valid and invalid viewing zones. Large negative values show the invalid viewing zones. Other θ values are the valid viewing zones. Thresholds should be given small negative values, such as -0.25:

$$\theta_{\text{valid}} - L_{\text{diff}}(\theta) > -0.25 \quad (2)$$

REPORTING:

The reported viewing area is the ratio of the valid viewing angle and the autostereoscopic angular range and may be reported as a number or a percentage:

$$A_{VA} = \frac{\theta_{\text{valid}}}{\theta_L + \theta_R} \quad (3)$$

Qualitative characterization to determine whether the field-of-view FOV is:

- connected (an area without interruptions, that is, the whole FOV area is a sweet spot), or
- discontinuous; sweet spots, invalid zones (inverse image, blended zones) are present.

The result is a graphical diagram of the valid viewing region, where undisturbed 3D view is provided, depicting the shape and structure of the FOV. See violet area in Fig 5.

COMMENTS: None.

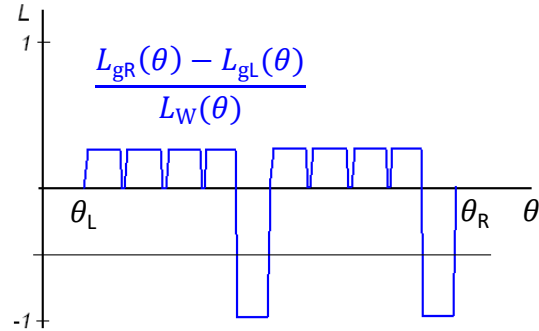


Fig. 4. Example of a graph for determining the valid viewing area.

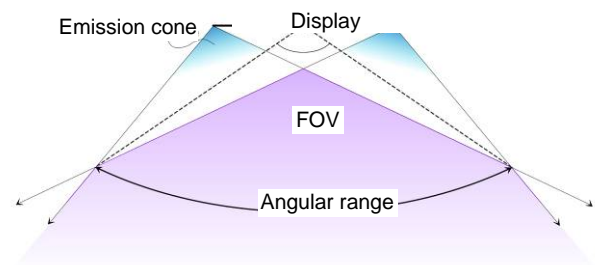


Fig. 5. Example of a valid viewing area.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Reporting example	
A_{VA}	80%



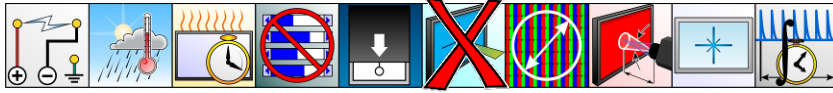
17.4.9 3D GEOMETRY DISTORTION

DESCRIPTION: This measurement quantifies the quality of the 3D scene reconstruction. It measures the capability of reconstructing a 3D geometry, when viewed from several angles. It is done by comparison with a vertical physical slit, which is used as a reference object.

Unit: %. **Symbol:** ΔS_{dist}

APPLICATION: This measurement can be applied to multi-view and light-field autostereoscopic displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

The scanning is performed with a high resolution conoscopic camera or a discrete LMD (with a measurement-field angle of $\Delta\theta \leq 0.25^\circ$ and preferably 0.2°) directed to the center of the screen, mounted on a stage moving on circle path, with a radius of the optimal viewing distance r_{DEP} . The rotary positioning apparatus has angular resolution of $\Delta\theta \leq 0.5^\circ$.

Test pattern: 3 pixels wide white vertical stripe on a black background displayed in front of the screen, at a distance d one tenth of the screen width.

Physical reference object: A black sheet half the height of the display with a 3-pixel wide, white vertical strip in the center placed in front of the screen at a distance d one tenth of the screen width.

PROCEDURE:

Measure the displacement ΔS between the center of the test pattern and the center of the physical reference object as a function of the measurement direction θ . Measurement range is the autostereoscopic angular range between angles θ_L and θ_R . A sample displacement measurement is shown in Fig. 3.

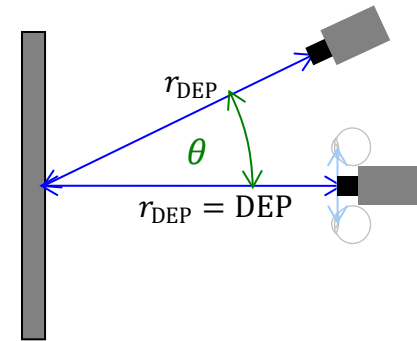


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

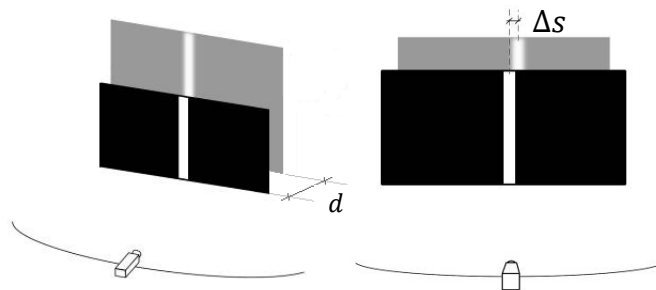


Fig. 2. Measurement method for characterizing 3D distortion.

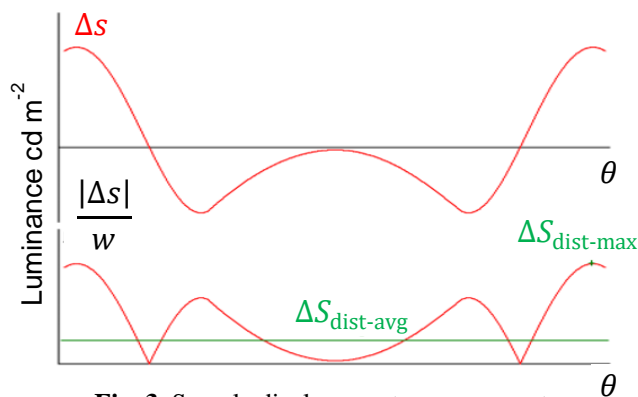


Fig. 3. Sample displacement measurement

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Measurement example	
θ_i	ΔS (mm)
42°	5.6
41°	5.9
40°	5.2
39°	5.0
...	
-41°	6.0
-42°	5.4

ANALYSIS:

Calculate the 3D distortion ΔS_{dist} value by normalizing the absolute value of ΔS displacement with the horizontal screen size W as a function of the angle (the camera in off-axis position):

$$\Delta S_{\text{dist}}(\theta_i) = \frac{|\Delta S(\theta_i)|}{W}$$

**REPORTING:**

The average rate of distortion $\Delta S_{\text{dist-avg}}$ or displacement over the FOV is:

$$\Delta S_{\text{dist-avg}} = \frac{1}{n} \sum_{i=1}^n \Delta S_{\text{dist}}(\theta_i)$$

Where n is the number of measurement points.

The maximum rate of distortion is $\Delta S_{\text{dist-max}}$ / displacement over the FOV is measured as the maximum of $\Delta S_{\text{dist}}(\theta_i)$.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

$\Delta S_{\text{dist-avg}}$	3.1%
$\Delta S_{\text{dist-max}}$	9.5%



17.4.10 MULTIVIEW SPATIAL BLUR EDGE WIDTH RATIO

DESCRIPTION: Measurement of the spatial blur edge width (BEW) ratio R per depth for multiview autostereoscopic display. When the depth d of a 3D object is non-zero, blur occurs at the area of binocular disparity when the number of views, N , is large. See reference for the origin of blur and the effect of depth on the blur width.

Unit: %; **Symbols:** N , BEW W , BEW Ratio R

APPLICATION: Multiview autostereoscopic display with a large number of views ($N > \sim 5$).

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



OTHER SETUP CONDITIONS: Use a 2-dimensional LMD, e.g. a CMOS or CCD camera, at the optimum viewing distance, z_{OVD} (see 17.4.5). Place the LMD on a translational stage that can move horizontally at least 6 cm. Use the test image shown in Fig. 1, i.e. two white boxes at zero and non-zero depth, respectively, on a black background. The non-zero depth can be at infinity or at any predetermined value, which shall be reported.

PROCEDURE:

8. Apply the 3D test image as the input signal. Determine the positions x_1 and x_N of view 1 and N , respectively, at $z = z_{OVD}$. See 17.4 for an explanation of the positions of view n of autostereoscopic 3D.
9. Select position x_R and $x_L (= -x_R)$ at $z = z_{OVD}$ around the center line of the display and as far as possible from $\pm x_1$ and $\pm x_N$ (Fig. 2). $x_R - x_L \equiv 6$ cm.
10. Place the 2D LMD at position x_L , perpendicular to the display. Capture image **L** at location x_L , which includes the left and/or right boundaries of the two white boxes of Fig. 1.
11. Move the LMD horizontally from position x_L to x_R . Capture the image **R**, which includes the same boundaries as image **L**.

ANALYSIS:

1. Derive the normalized luminance distribution along the horizontal lines $L0$ and $L1$, and $R0$ and $R1$, from image **L** and **R**, respectively. $L0$ and $R0$ cross the white box of zero depth, whereas $L1$ and $R1$ cross the white box of non-zero depth (see Fig. 3).
2. From the luminance distributions along $L0$ and $R0$, derive $H1$, which is the distance between the image **L** and **R** boundaries (see Fig. 4a). The unit of $H1$ is number of pixels in the captured image and it is related to the LMD translation of 6 cm from x_L to x_R .
3. Shift the relative position of image **R** (or image **L**) by the amount of $H1$ so that the black-white boundaries of the zero-depth white box for the **L** and **R** images coincide (Fig. 4a).
4. Calculate the width W at the black-white (or the white-black) boundary of white box of non-zero depth. W is defined as the horizontal pixel count corresponding to 10% and 90% of the normalized luminance (Fig. 4b). $W_{KW,L}$ and $W_{WK,L}$ are derived from image **L** along the horizontal direction of $L1$ at the left and right side of white box of non-zero depth.

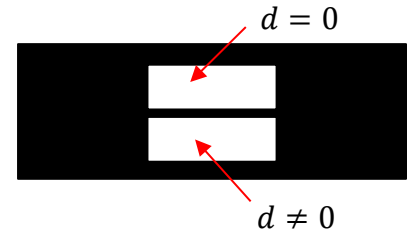


Fig. 1. 3D test image

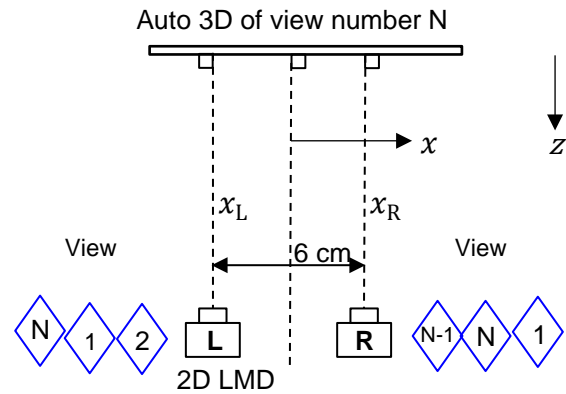


Fig. 2. Setup of 2D LMD

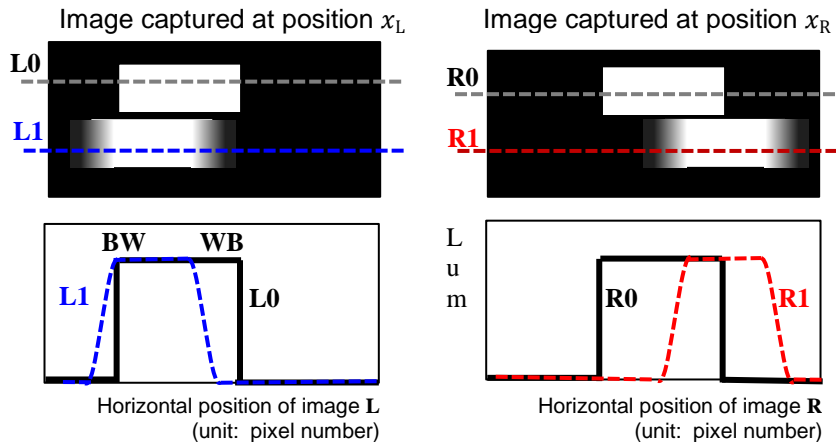


Fig. 3. Derivation of luminance distribution along the horizontal directions of $L0$, $L1$, $R0$ and $R1$.



$W_{KW,R}$ and $W_{WK,R}$ are similarly derived from image **R** along **R1**. **KW** and **WK** represent the transition from the black to the white area and vice versa, respectively.

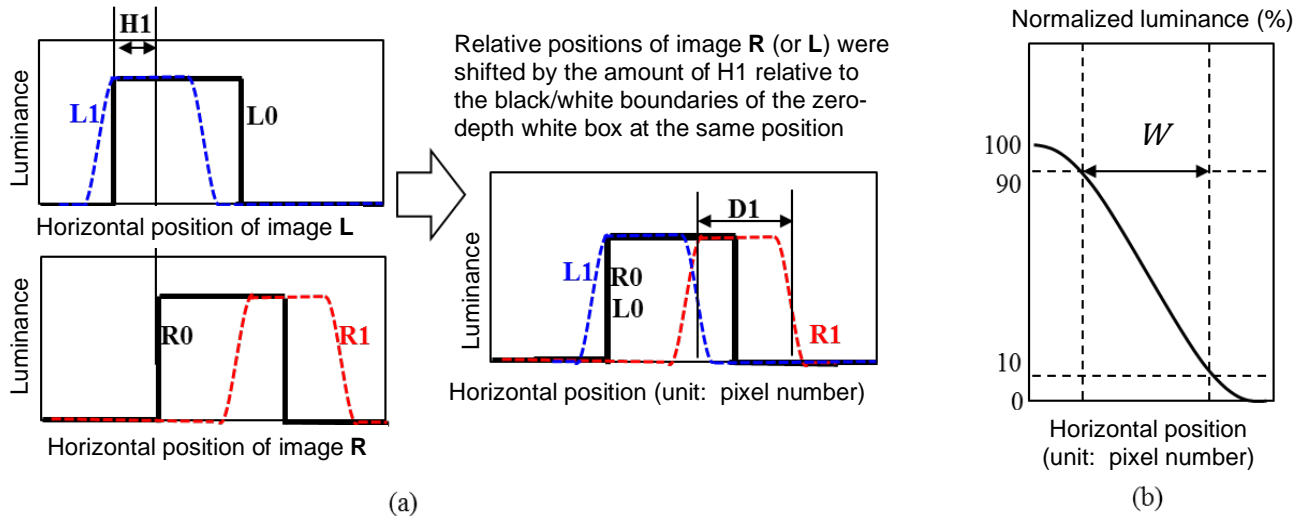


Fig. 4. (a) Relation of the positions of image **L** and **R**. (b) Definition of blur edge width **W**.

5. Calculate the average BEW of image **L** and image **R** as

$$W_{KW} = \frac{W_{KW,L} + W_{KW,R}}{2} \quad (1)$$

$$W_{WK} = \frac{W_{WK,L} + W_{WK,R}}{2} \quad (2)$$

6. Derive **D1** which is the pixel count corresponding to 50% luminance of BW or (WB) boundaries of image **L** and **R** (Fig. 4a).
7. Calculate the BEW ratio (%) as

$$R = \frac{W}{D1} \quad (3)$$

REPORTING: Report BEW and the BEW ratio (%) at BW and WB.

COMMENTS: (1) While Black and White are used as the intensity condition, low and high intensity can be used instead. (2) Values in unit of pixel number of the captured image can be converted into the actual length (unit: length) on the 3D display by multiplying by $6 \text{ cm}/H1$.

REFERENCE: Hong, H.K., "Influence of depth and 3D crosstalk on blur in multi-view 3D displays", *Journal of the SID*, Vol. 25(7), pp. 450-457 (2017)

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Table 1. Analysis example (unit: pixel number)			
H1	30	D1	21
$W_{KW,L}$	11	$W_{WK,L}$	12
$W_{KW,R}$	13	$W_{WK,R}$	13
W_{KW}	12	W_{WK}	12.5

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Table 2. Reporting example	
W_{KW} (unit: pixel number)	12
W_{WK} (unit: pixel number)	12.5
R_{KW} (%)	57%
R_{WK} (%)	60%



17.5 AUTOSTEREOSCOPIC LIGHT FIELD DISPLAYS

INTRODUCTION

While the sections above focused on the more commonly used stereo displays, we would like to focus in this section on light field displays, volumetric and holographic displays, as shown in the right side of Fig. 1 of the first page of this chapter. A very good overview of 3D displays is presented by Jason Geng [16]. We will not cover all the stereo display aspects, which are also covered by Abileah [3], and the methods for optical measurements. However, we would like to review a few of the 3D aspects of the human vision which will be later mentioned in the test procedures.

DEPTH CUES

We are viewing the world with both eyes, and there are several cues that help us realize the 3D effects:

1. **Accommodation** – each eye is focusing on the objects and the amount of strain in the lens of the eye is a measure of the distance to the object
2. **Convergence** – both eyes are gazing at the same object, but due to the finite interpupillary distance (IPD), the eyeballs are pointing in slightly different directions to achieve this. The angle between the two gazing directions is the convergence angle. Objects closer to the observer will have a larger convergence angle
3. **Motion parallax** – moving the head will cause a change in the observed location of the objects. Closer objects will change faster, whereas farther objects will hardly move with the head motion. (Some birds are moving their head sideways all the time for this purpose.)
4. **Binocular disparity** – the images of the same object will be at different positions on the retina in each of the eyes, due to the convergence. Closer objects will have bigger disparity (larger difference in the images between left/right eye retinas)

Not all these cues can be simultaneously realized by the displays. In particular, a common problem with stereo displays is the accommodation. While we are looking at a flat panel display, it is located at a fixed distance from our eyes, whereas the images of the rendered objects are expected to be at a different distance due to the convergence. Therefore, with stereo displays the major problem is the accommodation-convergence conflict, which causes nausea if it is too large and/or when viewed for long durations. Howarth [11] shows a plot of the relation between the convergence and accommodation on one hand, and the comfort zone on the other. It shows that stereo displays are limited to a convergence range of 0.21 ~ 0.74 m at a viewing distance of 1/3 m. This distance is applicable handheld devices, portable games, or desktop computer displays. Other effects that were studied by Kooi [9] shows that it is also important to have a low cross-talk to minimize eye-strain; it is recommended to have a maximum cross talk of 0.1% ~0.3% in a stereo-display with at least 100:1 contrast, and a convergence angle up to 40 arc-min, in order to achieve good depth perception. These effects are important attributes of stereo displays. Ideal volumetric and holographic displays do not have such problems, but these factors will be considered when making measurements.

TWO-DIMENSIONAL (2D) DEPTH CUES

There are several 2D cues which are assisting in the interpretation of image depth:

1. **Linear perspective** – objects at a distance appears to be smaller so a rectangle, for example, will look like an oblique angle trapezoid. Another example is the two rails of railway that appear to be converging at the horizon.
2. **Occlusion** – One object is hidden partially behind another object. The brain interprets this as if the full object is in front of the partially hidden object, and therefore is perceived as being closer than the other object.
3. **Shading** – Partial illumination of an object and shades next to it can give clues about the relative location. Sometimes the shade of one object falls onto another object. Variations in luminance across the object give clues about the surface curvature out of the image plane.
4. **Texture** – Small features on the object surface can assist in interpreting the shape of the object, including its depth.
5. **Prior knowledge** – of objects in different conditions, their motion behavior, and typical illumination and shading when separated or in a group can also assist depth interpretation.

While all these 2D cues are helpful for rendering 3D images on 2D displays, they are not sufficient for fully reproducing 3D situations. On the other hand, they can reduce the eye-fatigue in some cases of conflicts. A summary of previous findings by Geng [16] showed that 2D cues, which he calls psychological depth cues, are not significantly affected by the viewing distance. While the 3D cues, called physical depth cues, are affected much as a function of view distance.

CROSSTALK IN STEREO DISPLAYS

As explained in the introduction of chapter 17 under the title “Types of 3D Displays / Stereoscopic display”, the two images presented to the viewer are slightly different to reflect the binocular disparity in real life. The objects of the images are also



shifted horizontally to reflect the convergence. The assumption is that each eye sees totally different images. However, most optical systems for stereo have some amount of leakage of information of one eye into the other eye. The ratio of unintended image leakage into the intended information is the crosstalk. Woods [6] discussed in detail the different definitions of crosstalk and the methods for calculations. Abileah [19] showed the methods that is used in section 17.3.1, and is summarized in these formulas:

$$X_L = \frac{L_{LKW} - L_{LKK}}{L_{LWK} - L_{LKK}} \quad (1)$$

Where L is the measured luminance, subscript L is for the left eye, and KW means left image is black (K) and right image is white (W), and so on. Similarly, for the right eye we will have:

$$X_R = \frac{L_{RWK} - L_{RKK}}{L_{RKW} - L_{RKK}} \quad (2)$$

These formulas will not be applicable to light field or holographic displays since the separation of the images to the two eyes are not so clear for each view orientation. Therefore, we need a new technique to estimate the depth perception, which is not based on the stereo effect, and its “purity” measured by the crosstalk. This will be discussed below.

DEPTH PERCEPTION AND RESOLUTION

In light field displays, as well as in volumetric and holographic displays, the images include the depth perception. Besides the stereo effect they include convergence and binocular disparity. However, this depth will not be visible if the resolution of the image is not adequate. Therefore, people consider the resolution measurement as a metric for the quality of the 3D effect and depth perception. The measurement is done at a specified viewing distance from the display screen.

The resolution can be measured at one viewing distance for several depth values of the presented information. For each depth value a sinusoidal pattern is displayed, and the pattern is measured at the targeted view distance. Then we compare it to the reference pattern. This method is similar to the measurement of modulation transfer function (MTF). Getting the ratio of the measured pattern to the reference gives the MTF number. Repeating this test at several image depth values and plotting the MTF for each depth, will give us a way to measure the depth perception. This method is described in v1.03 of IDMS [1], section 17.5.4, and is based on several papers [20, 21, 22]. A more detailed description and instructions will be described below.

The logic behind this test for light field, volumetric and holographic displays is that the image pairs are continuous, and the image per eye is separated from the neighboring image by the eye relief defined by the iris. In medium light levels the eye pupil diameter will be about 5 mm. This is the area in which the image should fall, and it should be without mixing with unintended information from neighboring image. In high-resolution field-of-light Displays (FoLD), such as light field displays, the separation will also be good and therefore the depth perception will improve.

LIGHT FIELD DISPLAYS

Light field displays are based on the optical principle that instead of focusing the images to each eye separately at a given distance, the light beams emanating from the display are parallel beams and your eyes can view only the beams that are directed to them. The selection of beams will depend in space by the distance between the eyes (IPD - interpupillary distance). Figure 1 illustrates this graphically [1]. In both cases in this example a 1D array of cylindrical lenticular lenses is used. This principle can be extended to a 2D array of lenticular lenses where stereo image rendering is possible even if the display is rotated 90° around its surface normal axis. For autostereoscopic imaging, a 1D lenticular lens array should be adequate, though. In a light field display, the same pixels will be seen by the same eye as you move from right to left or from left to right. The condition that has to be met is that the interpupillary distance IPD is maintained and matching the pixel separation. Therefore, in this case (and also in the multi-view case) it is important to have a high-resolution display with a sufficiently many pixels, which allows separate, clear images to both eyes.

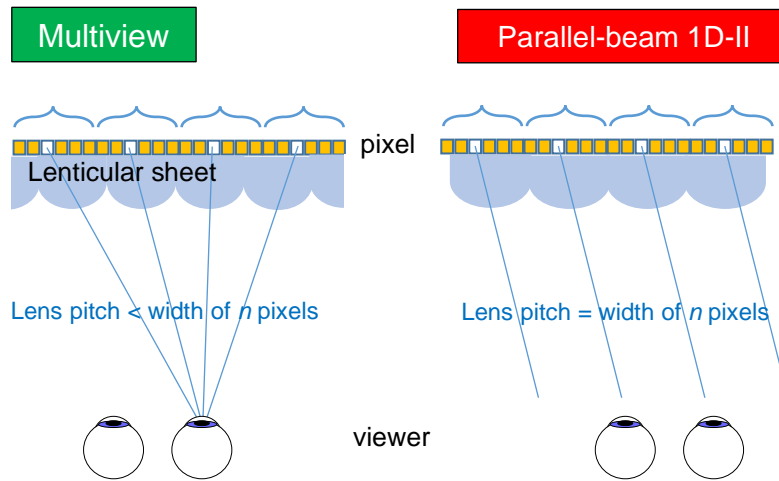


Fig. 1. Comparison of multi-view and light-field display horizontal sections. II=integral imaging, an autostereoscopic and multiscopic three-dimensional imaging technique that captures and reproduces a light field by using a two-dimensional array of microlenses, sometimes called a fly's-eye lens, normally without the aid of a larger overall objective or viewing lens [28].

LIGHT FIELD DISPLAYS - BACKGROUND

Light rays that are traveling in space, will hit a surface. This surface can be, for example, an array of lenses. Figure 2 shows examples of rays that are hitting two types of surfaces:

1. Diffused surface (left side), which is scattering the rays to many directions – this generates a 2D image, and
2. Clear surface (on the right), which transfer the rays without change – this generates a 3D image, since we look at the origin of the rays, including their depth.

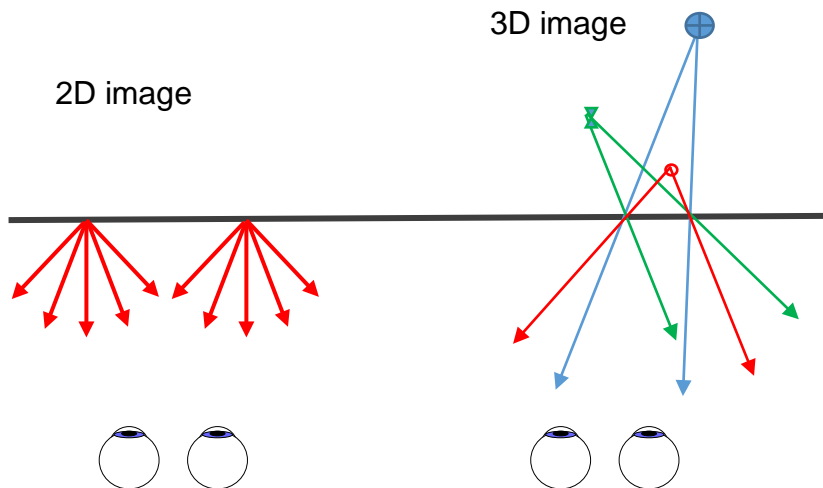


Fig. 2 Rays hitting two types of surfaces: 2D diffuse image (left); 3D clear, redirecting image (right)

In order to trace back the rays, the following notation is used:

1. The hitting location on the surface (x, y)
2. The orientation of the rays emanating from the screen (θ, φ)

Therefore, we can describe the surface of light field as $F(x, y, \theta, \varphi)$, a function that describes the surface with all its rays coming from each point and their directions. Example of rays are shown in Fig. 3.

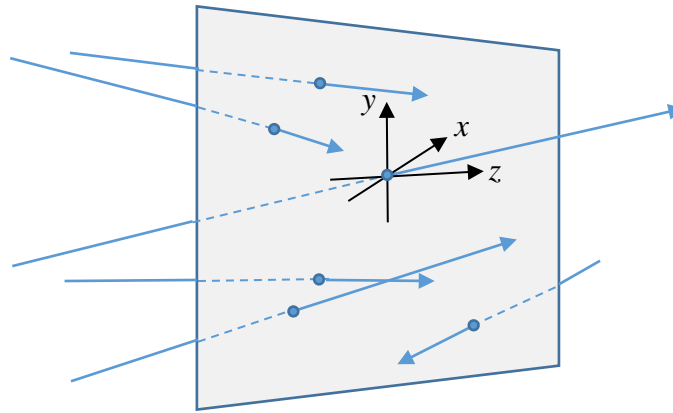


Fig. 3. Light field of rays coming out of a surface; each ray crosses the plane at a different location and has a different direction

This notation is taken from the introduction by Kovacs in the IDMS v1.03 [1].

THE PLENOPTIC FUNCTION

Similar to the notation above, a light field can be described by the plenoptic function for each ray. This is described by Jason Geng [16] as a function of:

1. The location from which the light is emanating (x, y, z) – in space
2. The orientation of the ray (θ, φ) – polar coordinates
3. The wavelength of the light (λ)
4. The time of observation, in the case of moving images (t)

Therefore, the plenoptic function is: $P(x, y, z, \theta, \varphi, \lambda, t)$

EFFECT ON MEASUREMENTS

The ray tracing described above shows that there might be a difference in measurement techniques between multi-view displays and light field displays. This is described by Koike [5] as differences in ray space. This paper explains that the multi-view displays can be measured at close proximity with a Fourier (conoscopic) camera. This will give the luminance and chromaticity readings at the proper angles, since the rays are emanating in all directions and can be measured at the sweet spots, and in between. For light field displays, however, it will not work since the single ray direction will appear as single point and will not give a complete picture. Therefore, Koike *et al* recommend using a high-resolution camera and a method similar to a modulation transfer function (MTF) measurement. Koike *et al* wrote the section in IDMS v1.03 [1] that describes the MTF measurement. A more detailed procedure will follow in this document. Therefore, for light field displays and any other FoLD, we propose to use a high resolution camera, since all of them have similar space of rays as defined by Koike [5]. Note: the entrance pupil of the optics of the camera has to be of a size similar to that of the human eye, e.g. typically 5 mm in diameter. This is critical when making the resolution measurements.

We have to mention that in the light field display with lenslets, there is a possibility to take the angular distribution of the rays coming from a single lens, using the conoscopic camera at close proximity and aligned carefully with the center of the lens. This is very complex, but it can be done. This will give a part of the space of rays' map for the display for evaluation.

INSTRUMENTS FOR MEASUREMENTS

The measurement devices that will be used for the special tests for FoLD are similar to the ones defined in IDMS v1.03 [1] section §3.1:

LUMINANCE SPOT PHOTOMETER

1. Has optics with focusing capability and a well-defined aperture angle (e.g. 2°).
2. Sufficient system accuracy for the requirements and for the spectrum of the display to be measured (see Appendix A1.1 of this document) .
3. The repeatability should be within the requirements for the duration of the measurement.

CONTACT-TYPE LUMINANCE METER

A sensor without focusing optics attached directly to the surface of the display (often used for monitor calibration). Since this type of sensor collects light from many angles with an undefined aperture angular distribution, it will in most cases produce incorrect results for 3D displays and is therefore not recommended.



COLORIMETER

1. Can be either a spectroradiometer or triple-sensor with spectral characteristics similar to the 1931 CIE color matching functions.
2. Requirements same as for the luminance spot photometer (see above). Luminance is the same as Y of the measured XYZ tristimulus values.
3. The expanded uncertainty is defined in the IDMS v1.03 [1] in appendix A1.1 and should be within the requirements of the measurement.

ARRAY DETECTORS (CAMERAS)

1. Photometric cameras will be the most useful instrument for the type of displays that we intend to measure.
2. This includes digital cameras, i.e. a 2D array of sensors of either CCD or CMOS type. The sensors should have a system accuracy according to the requirements for the measurement, and for the spectral power distribution of the display to be measured (see Appendix A1.1 of this document)
3. The cameras have focusing optics and have to be compensated for non-uniformity (both optical vignetting, and sensors non-uniformity).
4. The number of pixels in the camera should be sufficiently high, in most cases at least $3\times$ spatial oversampling of the display imager, preferably $10\times$.
5. One of the main issues with cameras is the Moiré effect, which should be avoided by either 1) adjusting the measuring distance (effectively changing the amount of oversampling), 2) rotating the camera around the optical axis by maximum $\pm 9^\circ$, or 3) adjusting the focal length of the photometer by maximum $\pm 5\%$. Rotation is the recommended method for avoiding Moiré.
6. As mentioned earlier, the entrance pupil of the lens of the camera should be similar to the human eye, with typical 5 mm opening. This is critical for the resolution of the testing.

The repeatability should be within the requirements for the duration of the measurement.

BASIC TESTS

In testing the 3D displays which are field of light displays (FoLD) we should include basic test procedures, as well as unique tests for FoLD. Among the basic tests are:

Luminance uniformity:

1. Local uniformity (including Mura)
2. Color uniformity
3. Color differences in small area
4. Contrast ratio
5. Angular luminance drop
6. Angular color shift
7. Temporal variations, like visible flicker
8. Video smearing
9. Artifacts – visible

For all these basic features are already established test procedures, most of them are summarized in version 1.03b of the IDMS[1]. In the following sections we will discuss the specific test procedures for field of light displays (FoLD) like the light field displays.

TEST PATTERNS

In order to perform several tests, we would like to use test patterns.

Version 1.03b of the IDMS [1] specifies several patterns which are described in Section 17.6.1. However, since the focus of that section is on stereoscopic displays, the patterns include stereo pairs for left/right eyes.

FULL FIELD PATTERNS

Image pairs are not necessary for FoLDs, but the full field patterns need to be displayed at several depths. We will use the notation described in 17.6.3.

VISUAL INSPECTION

Before performing a large set of measurements, it is recommended to display some test patterns and examine the display for functionality and integrity. The images should therefore include depth elements. Test patterns for stereo displays are available in version 1.03b of the IDMS[1] and include three types of patterns: 1) alignment tools, 2) visual inspection, and 3) patterns for measurements. These patterns are not necessarily applicable to light field displays.

TYPES OF PATTERNS FOR VISUAL INSPECTION

A set of images and patterns are required also for FoLDs:

1. Alignment tools/patterns can help during adjustment of the display system, but also can help in visual inspection, and verification that the system is “behaving” as expected.



2. Typical visual patterns can vary from display to display but they should all include depth perception. The hedgehog pattern presented in 17.6.4 is a rotating structure, which also moves around at different depths. It covers significant situations and can be viewed from several directions.
3. Lee et al [24] are using a visual presentation for a real depth measurement. They put a triangle and a circle at different depths and let the viewer determine which pattern is in focus. The depth difference between the two patterns is controlled by the simulation program. This method is a quick way of estimating depth in FoLDs but does not provide any objective metric.
4. Test patterns for measurements can also help by looking on them visually. Sweeping through them can show if there are issues, like missing sections of the image, gross non-uniformity, or other problems.

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17.5.1 LIGHT FIELD ANGULAR RESOLUTION

ALIAS: depth range, depth of field

DESCRIPTION: Measure the angular resolution as a function of horizontal viewing angle of a multi-view display at the display center. We will use these profiles to determine the maximal displayable depth of field. **Units:** degree, meter. **Symbols:** $\Delta\theta$, D_F



APPLICATION: This measurement can also be applied to light-field autostereoscopic displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).

OTHER SETUP CONDITIONS: Use an LMD with a measurement-field angle of $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is centered on the neutral image (depth zero) at normal angle and at a radius r_{DEP} of the design eye position (DEP). The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ (preferably $\Delta\theta \leq 0.2^\circ$). Test patterns at the neutral view depth to be used are two-view images designated left eye/right eye: (a) black/white, and (b) white/black.

PROCEDURE:

- Measure the autostereoscopic angular range (§17.3.5). Values are θ_L and θ_R for the left and right sides.
- Measure the luminance profile of the display when all the views are white (L_W).
- Measure the luminance profile of the display when all the views are black (L_K).
- Measure the luminance profiles for individual views $L_i(\theta)$, $i = 1, 2, \dots, n$ with the view image i white and the other views' image black. The sum of the individual view luminance profiles should be approximately equal to the stereoscopic luminance profile measured when all views are white.

ANALYSIS:

- Count the number of local maximum luminance values, N_{KW} , within the autostereoscopic viewing angular range as shown in Fig. 2 of 17.4.6 for the black/white test patterns.
- Count the number of local maximum luminance values, N_{WK} , within the autostereoscopic viewing angular range as shown in Fig. 1 for the white/black test patterns.

REPORTING: The reported angular resolution value is $\Delta\theta$. The angular resolution $\Delta\theta$ is determined by dividing the sum of θ_L and θ_R by the number of periods between the local maxima:

$$\Delta\theta = \frac{\theta_L + \theta_R}{N_{WK} + N_{KW} - 1} \quad (1)$$

Maximal displayable depth of field, D_F , is closely related to the angular resolution. It can be calculated from the pixel size d_{pix} and the angular resolution $\Delta\theta$. D_F can be calculated by dividing the pixel size d_{pix} of the display by the tangent of the angular resolution:

$$D_F = \frac{d_{\text{pix}}}{\tan \Delta\theta} \quad (2)$$

COMMENT: Aliasing of the image (and/or other artifacts, depending on the type of the display) will occur.

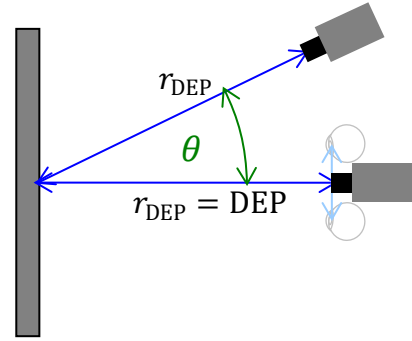


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:

$L_{KW}(-49.6^\circ)$	63
$L_{WK}(-46.4^\circ)$	75
:	
$L_{KW}(-29.8^\circ)$	120
$L_{KW}(-23.4^\circ)$	138
:	
$L_{KW}(18.8^\circ)$	144
$L_{KW}(25.8^\circ)$	135
$L_{WK}(29.2^\circ)$	125

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

$\Delta\theta$	1.3°
D_F	0.5m



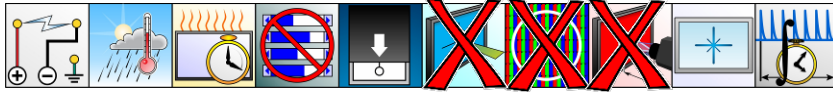
17.5.2 LIGHT FIELD VALID VIEWING RANGE

ALIAS: Field of view, viewing freedom

DESCRIPTION: Measure the field of view (FOV) and the valid viewing range inside the FOV of a light field display using quantitative and qualitative methods. The qualitative measurement method involves scanning in small angular increments to determine the valid viewing range, within which the display delivers the correct sign of the disparity between any pair of views. The scanning can be done either with a spot photometer LMD mounted on a moving stage capable to cover the presumable FOV range, or with a high-resolution conoscopic camera. Rotating the sample (the display) around the LMD is possible, but less practical. **Unit:** percent (%). **Symbol:** V_{VA} .

APPLICATION: This measurement can also be applied to multi-view autostereoscopic displays.

SETUP: As § 3.2).



OTHER SETUP CONDITIONS: Use an LMD with a measurement field angle $\theta_{MFA} \leq 0.25^\circ$ and preferably $\theta_{MFA} \leq 0.2^\circ$. The LMD is centered on the screen normal at a radius r_{DEP} of the designated eye position. The LMD is rotated about the center maintaining the radius r_{DEP} and pointing at the screen center using a rotary positioning apparatus with angular resolution $\Delta\theta \leq 0.5^\circ$ (preferably $\Delta\theta \leq 0.2^\circ$).

This measurement requires two parallel LMDs separated by the standard Inter-Pupillary-Distance (IPD). For adults it is typically 6.25 cm (some use 6.5 cm.). Both LMDs are directed to the center of the screen. Since the LMDs are parallel, they will focus slightly left (-0.5 IPD) and slightly right (+0.5 IPD) from the display center. Alternatively, one LMD can be used in the two locations separated by the IPD (~6.5 cm). Measuring luminance profile will use a full white image test pattern.

In the case of discrete views, we need to identify the valid viewing area (the correct disparity). We should use steps of luminance pattern. In this case we use monochrome views, each with linear steps of luminance from 0 to 255. The value of luminance steps is calculated as 255 divided by the number of views. The luminance pattern should have 0 on the leftmost view and 255 on the rightmost side.

For the light-field, the method to identify valid viewing area (correct disparity) is: Use a test pattern with an angularly monotonic increasing grey-scale pattern (e.g. from 0 to 255). Scan the valid area of correct disparity. The border is at the first inflexion point of the intensity values measured in the scanning direction. The first pattern has 0 on the left side and 255 on the right side.

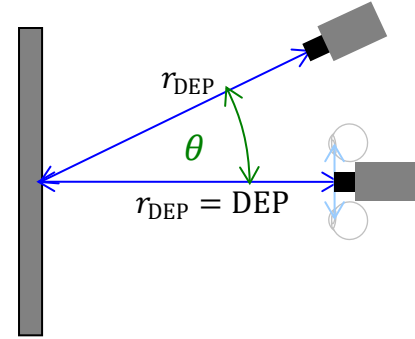


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

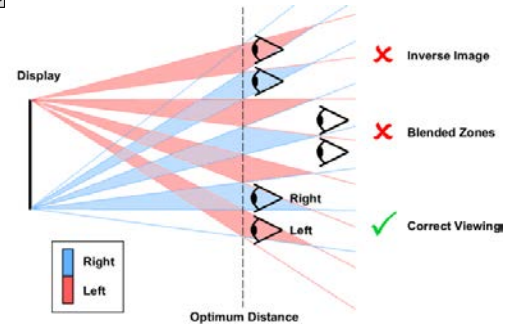


Fig. 2. Example of zones having valid and invalid disparity.

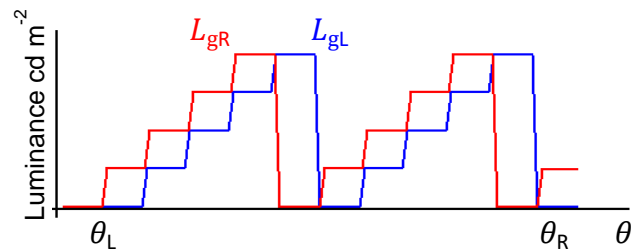


Fig. 3. Example of measured grayscale profiles.

**PROCEDURE:**

Perform the following measurement steps to measure the viewing freedom:

1. Measure the autostereoscopic angular range; θ_L and θ_R for the left and right sides. Further measurement steps must be done within the range of θ_L to θ_R .
2. Measure the luminance profile $L_W(\theta)$ of the display when all the views are white.
3. Measure the left and right luminance profiles $L_{gL}(\theta)$ and $L_{gR}(\theta)$ of the display when the grayscale test pattern is displayed. A sample measurement is showed in Fig. 3.

ANALYSIS:

4. Normalize the measured grayscale luminance data by the full white luminance data.
5. Calculate luminance difference between the right and left detector data (see example graph in Fig. 4.):

$$L_{\text{diff}}(\theta) = \frac{L_{gR}(\theta) - L_{gL}(\theta)}{L_W(\theta)} \quad (1)$$

6. The resulting graph shows the valid and invalid viewing zones. Large negative values show the invalid viewing zones. Other θ values are the valid viewing zones. Thresholds should be given small negative values, such as -0.25:

$$\theta_{\text{valid}} - L_{\text{diff}}(\theta) > -0.25 \quad (2)$$

REPORTING: The reported viewing area is the ratio of the valid viewing angle and the autostereoscopic angular range and may be reported as a number or a percentage:

$$A_{VA} = \frac{\theta_{\text{valid}}}{\theta_L + \theta_R} \quad (3)$$

Qualitative characterization to determine whether the field-of view FOV is:

1. Connected (an area without interruptions, that is, the whole FOV area is a sweet spot), or
2. Discontinuous; sweet spots, invalid zones (inverse image, blended zones) are present.

The result is a graphical diagram of the valid viewing region, where undisturbed 3D view is provided, depicting the shape and structure of the FOV. See light purple area in Fig. 5.

COMMENTS: None.

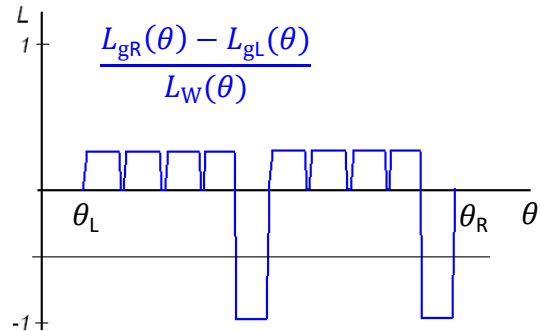


Fig. 4. Example of a graph for determining the valid viewing area.

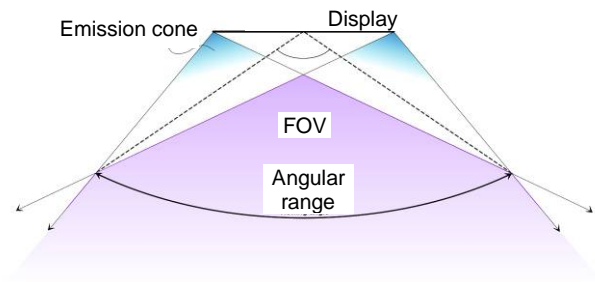


Fig. 5. Example of a valid viewing area.

—SAMPLE DATA ONLY—	
Do not use any values shown to represent expected results of your measurements.	
Reporting example	
A_{VA}	80%



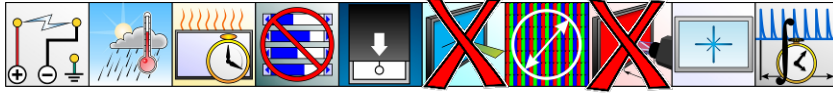
17.5.3 LIGHT FIELD 3D GEOMETRY DISTORTION

DESCRIPTION: This measurement quantifies the quality of the 3D scene reconstruction. It measures the capability to reconstruct a 3D geometry, when viewed from several angles. It is done by comparison with a vertical physical slit, which is used as a reference object.

Unit: %. **Symbol:** ΔS_{dist}

APPLICATION: This measurement can be applied to also to multi-view autostereoscopic displays.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS:

The scanning is performed with a high resolution conoscopic camera or a discrete LMD (with a measurement-field angle of $\Delta\theta \leq 0.25^\circ$ and preferably 0.2°) directed to the center of the screen, mounted on a stage moving on circle path, with a radius of the optimal viewing distance r_{DEP} . The rotary positioning apparatus has angular resolution of $\Delta\theta \leq 0.5^\circ$.

Test pattern: 3 pixels wide white vertical stripe on a black background displayed in front of the screen, at a distance d one tenth of the screen width.

Physical reference object: A black sheet half the height of the display with a 3-pixel wide, white vertical strip in the center placed in front of the screen at a distance d one tenth of the screen width.

PROCEDURE:

Measure the displacement ΔS between the center of the test pattern and the center of the physical reference object as a function of the measurement direction θ . Measurement range is the autostereoscopic angular range; angles θ_L and θ_R . A sample displacement measurement is shown in Fig. 3.

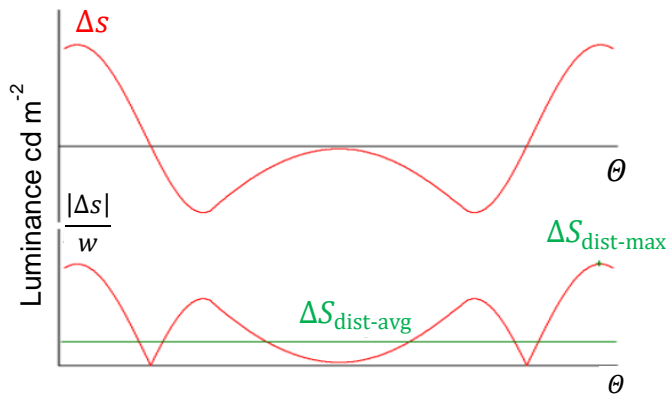


Fig. 3. Sample displacement measurement

ANALYSIS:

Calculate the 3D distortion ΔS_{dist} value by normalizing the absolute value of ΔS displacement with the horizontal screen size w as a function of the angle (the camera in off-axis position):

$$\Delta S_{\text{dist}}(\theta_i) = \frac{|\Delta S(\theta_i)|}{w}$$

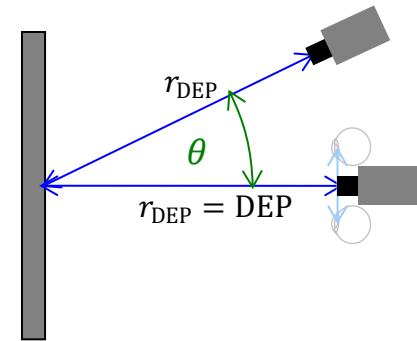


Fig. 1. Luminance angular scan by LMD with radius maintained at design eye position distance.

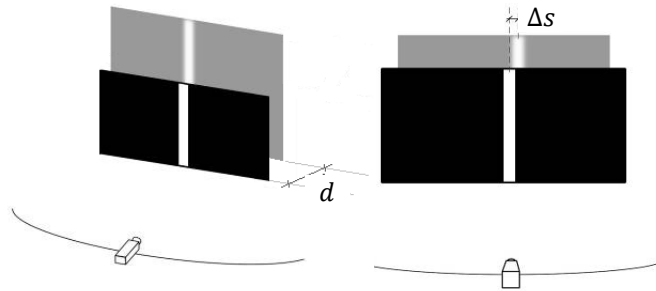


Fig. 2. Measurement method for characterizing 3D distortion.

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.	
Measurement example	
θ_i	ΔS (mm)
42°	5.6
41°	5.9
40°	5.2
39°	5.0
...	
-41°	6.0
-42°	5.4

**REPORTING:**

The average rate of distortion $\Delta S_{\text{dist-avg}}$ or displacement over the FOV is:

$$\Delta S_{\text{dist-avg}} = \frac{1}{n} \sum_{i=1}^n \Delta S_{\text{dist}}(\theta_i),$$

where n is the number of measurement points.

The maximum rate of distortion is $\Delta S_{\text{dist-max}}$ / displacement over the FOV is measured as the maximum of $\Delta S_{\text{dist}}(\theta_i)$.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

$\Delta S_{\text{dist-avg}}$	3.1%
$\Delta S_{\text{dist-max}}$	9.5%



17.5.4 LIGHT FIELD AUTOSTEREOSCOPIC IMAGE RESOLUTION

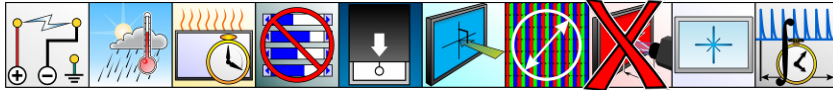
ALIAS: 2D equivalent resolution

DESCRIPTION: Quantitative characterization of displays through the total number of controlled light beams / pixels. Measure the performance of the resolution per depth for autostereoscopic displays.

Units: Cycles per mm, Pixels. **Symbols:** R_{total} , β_{3D} , β_{2D} .

APPLICATION: This measurement can be applied to light field autostereoscopic displays or integral-type emissive autostereoscopic displays.

SETUP:



OTHER SETUP CONDITIONS:

1. Fixed measurement camera conditions (e.g. CCD or CMOS):
 - a. High resolution ($>3\times$, preferably $10\times$ resolution of the display's optical elements)
 - b. Less than 5% geometrical distortion, optionally achieved by geometric correction
 - c. Calibrated gamma $\gamma = 2.2 \pm 0.1$.
 - d. Depth of field (DOF) larger than the depth range of the evaluation.
 - e. DOF at least of distance between the display surface and maximal depth of the displayed 3D images.
 - f. Focal length set at the depth of the 3D images and kept constant throughout measurement.
2. Configurable measurement conditions (test patterns):
 - a. Sinusoidal pattern with depth (stereoscopic image). Normally, test patterns are provided by the supplier.
 - b. If you know the relation between the display panel and the optical system, you can create test patterns using $I = \frac{A}{2}(1 + \sin \omega x)$, where A , ω , and x is the maximum digital level, radian frequency, and position, respectively.
3. Measurement geometry:
 - a. Camera position: Design eye position (DEP), if provided by the supplier.
 - b. Camera direction: same as the direction of main use (normally perpendicular to the display surface)
 - c. Captured area: whole display area. For high resolution displays, a region of interest (ROI) may be required in order to meet condition 1a above.



Fig. 1. Examples of sinusoidal test patterns

PROCEDURE:

1. Display a horizontal sinusoidal test pattern at a specified depth.
2. Capture the image with the calibrated high-resolution camera.
3. Repeat for test patterns of different spatial frequencies.
4. Repeat 1-3 for different depths
5. Repeat 1-4 vertical, diagonal (see Fig. 1), and optionally for other directions.

**ANALYSIS:**

1. For light field displays not based on lenses and without design eye position/optimum viewing distance, image resolution shall be expressed in number of pixels.
2. For lens-based light field displays, the pixel size shall be determined by the lens size.
3. Normalize the depth coordinate by display diagonal size in mm: z/D
4. Report the resolution at z distance in cycles per millimeter for lens-based displays and otherwise as the 3D pixel fraction of number of 2D pixels.
5. Average the sinusoidal pattern response in a direction perpendicular to the wave vector of the pattern
6. Calculate the contrast ratio at different depths and normalize it to the pattern recorded at $z/D = 0$ (see Fig. 3).
This procedure is equivalent to measurement of the modulation transfer function (MTF) in each depth position.
7. Plot the minimum points in contrast ratio vs. depth plot (Fig. 4). This plot corresponds to the resolution limit depth at the evaluated resolution.

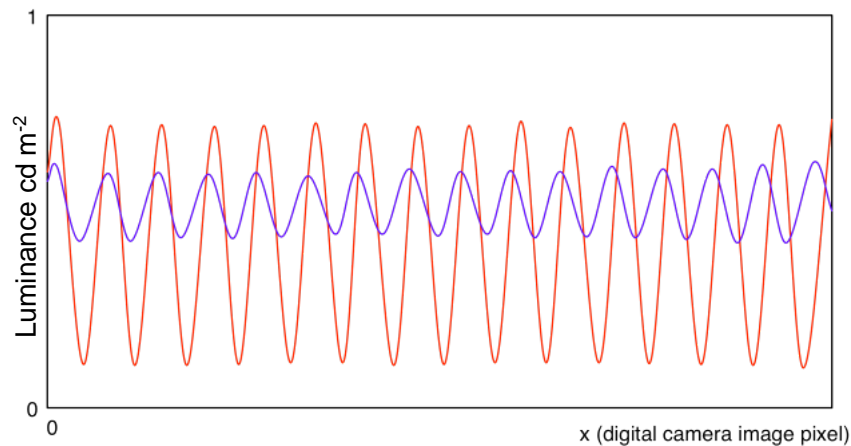


Fig. 2 Examples of fitting curves of displayed sinusoidal patterns. Red and blue plots are measured luminance of sinusoidal wave pattern at $z = 0$ (red) and $z = 0.03D$ (purple), respectively.

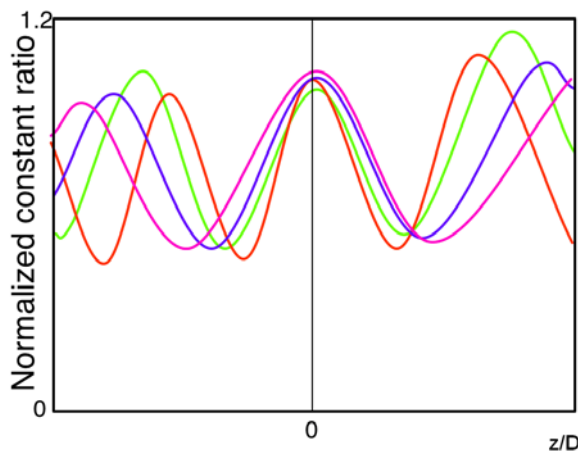


Fig. 3 Example of the normalized contrast plots.

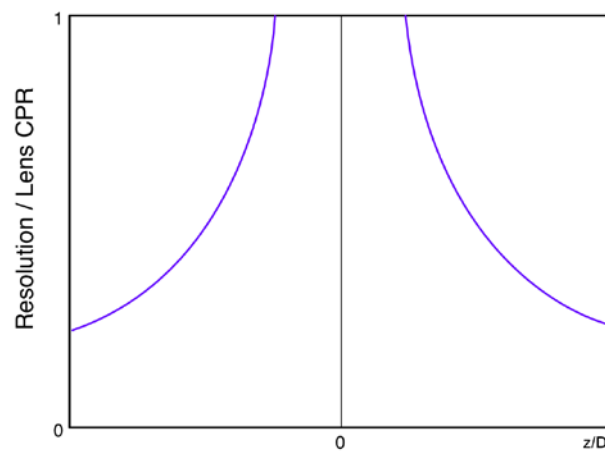


Fig. 4 Examples of the resolution limit versus depth.

**REPORTING:**

The reported relative frequency value β_{3D} is 2D image resolution at depth z . These are the values from Fig 4. The reported 2D equivalent resolution is β_{2D} .

In the horizontal direction:

$$\beta_{2D-H} = \beta_{3D}(z = 0) \frac{w}{d_{\text{pix}}}$$

In the vertical direction:

$$\beta_{2D-V} = \beta_{3D}(z = 0) \frac{h}{d_{\text{pix}}},$$

where: w – display width; h – display height, d_{pix} – pixel width

In case of flat screen-based systems, the total resolution R_{total} equals the number of pixels that the flat screen is able to control. In case of projection-based light-field displays, the total number of light beams equals the sum of light beams emitted by each projection engine. That is:

$$R_{\text{total}} = R_x R_y N_{\text{proj}},$$

where: R_{total} is the total number of pixels; R_x is the number of pixels in the horizontal x -direction; R_y is the number of pixels in the vertical y direction; and N_{proj} is the number of projections.

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—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example

β_{3D}	$0.4 \text{ }^z/D$	0.2
β_{3D}	$0.2 \text{ }^z/D$	0.3
β_{3D}	$0.1 \text{ }^z/D$	0.5
β_{3D}	$0.05 \text{ }^z/D$	0.8
β_{3D}	$0 \text{ }^z/D$ ($z = 0$)	1
β_{3D}	$-0.05 \text{ }^z/D$	0.8
...
β_{2D}		1280x720 px
R_{total}		70 M Pixels



17.5.5 LIGHT FIELD DEPTH – LEE'S METHOD

ALIAS: Visual depth assessment

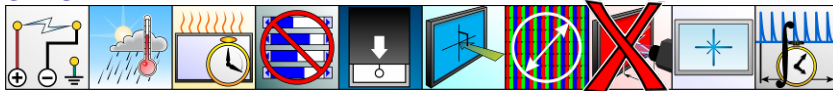
DESCRIPTION: As discussed, the depth of stereo displays is mostly influenced by the crosstalk. For light-field and other Field of Light Displays (FoLDs) there is no separation between left and right eye. The depth perception is coming from a separation to each eye by directional rays. Therefore, this is mostly influenced by the resolution of the display, the ability to control the rays in space, and somewhat by the display contrast.

Lee et al [1] proposed to use computer-generated images, also called computational integral imaging reconstruction (CIIR), of a triangle and a circle shown side by side. The CIIR software controls the depth difference between the triangle and the circle. Then it changes gradually the depth difference and position the images. The viewer has to specify which image is in focus, and which not. If there is big difference between focused and non-focus images it will indicate that there is a good depth separation in the display.

Unit: Millimeter, **Symbol:** δ_{3D} .

APPLICATION: This measurement can be applied to light field autostereoscopic displays or integral-type autostereoscopic displays that emit light. It can also fit volumetric display that emit or reflect light, and to holographic displays.

SETUP:



OTHER SETUP CONDITIONS:

1. Use the image generation of the display under test.
2. Display a circle in one depth (D_{11}) – using the CIIR driving
3. Display next to the circle a triangle in a different depth (D_{22}) – using the CIIR driving.
4. Refer to Fig. 1.

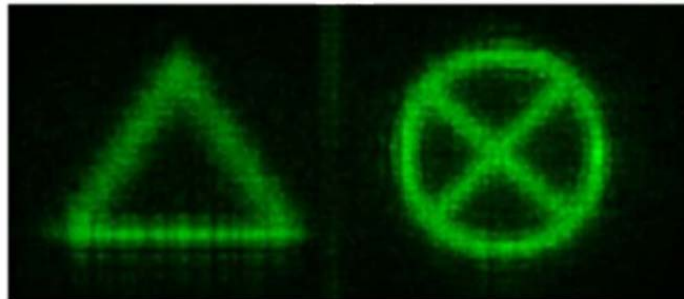


Fig. 1. Triangle at depth (D_{22}) and Circle at depth (D_{11}) – generated by CIIR driving

PROCEDURE:

1. Using the CIIR, display a circle at depth D_{11} .
2. Using the CIIR, display a triangle next to the circle but at a different depth D_{22} .
3. Adjust the depth of the circle (D_{11}) until it is in focus (visually).
4. Adjust the triangle to be not in focus and record the depth (D_{33}).
5. Gradually readjust the triangle focus, until it is in similar focus to the circle, then record the depth (D_{22}).

ANALYSIS:

1. Calculate the depth between the circle and the triangle:

$$\delta_{3D} = D_{22} - D_{11} \quad (1)$$

2. Repeat the process few times (e.g. five times) and average the δ_{3D} numbers to report one average number.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Analysis example:

δ_{3D}	5 mm
---------------	------

**REPORTING:**

Report the depth difference δ_{3D} between the circle and the triangle when both are in focus. This will be the average of at least five measurements.

COMMENTS:

This method is relying on visual assessment, however, the driving of patterns (circle and triangle) are controlled by the software. This method is giving an estimate for the depth sensitivity.

REFERENCE:

- [1] Lee, S., Nam, J., Chang, E-Y, Lee, S-K, Moon, K., Kim, J, “Measurement of Depth Representation using Integral Imaging for Quality Evaluation of Computer-generated Hologram”, Proc. of SPIE Vol. 9117



17.6 CHAPTER APPENDIX: 3D & STEREOSCOPIC DISPLAYS

Because the following sections are directly related to stereoscopic displays, we present them here rather than in the main appendix at the end of the IDMS document.

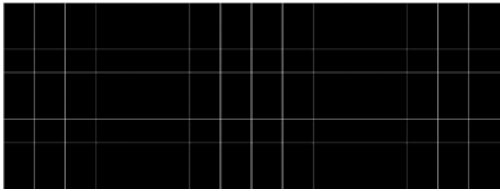
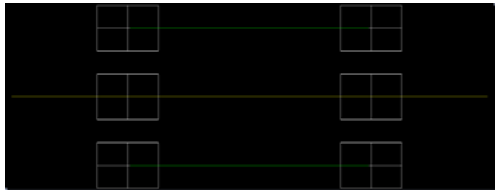
17.6.1 STEREOSCOPIC DISPLAY PATTERNS



Stereoscopic displays are based on the principle of binocular disparity, the cue for stereopsis, which derives from the fact that the two eyes are horizontally separated on the head. This separation between the eyes means that the two eyes view the world from a slightly different perspectives, called binocular parallax, which in turn creates lateral shifts in the retinal position of corresponding monocular images (i.e., binocular disparity). Therefore, in testing these displays we have to emulate the natural situation and generate separate images to each eye. The following set of basic testing patterns will include left-eye and right-eye images. Depending on whether the DUT includes rendering of the right/left input image, the patterns have to be modified when applied to the display in order to create the separation between the two eyes' views. Even if rendering is included, the stereo encoding of the input image format may be different, e.g. temporal multiplexing at double frame rate or side-by-side encoding at twice the monoscopic image width. In some types of auto-stereoscopic display renderings, the two eyes' views are fed into the odd and even columns or rows of the display, behind the pattern of parallax barriers, lenticular lenses, or spatially modulated polarizers or color filters. In time-multiplexed displays the two eyes' views are rendered across sequential frames. In spatially multiplexed displays, wherein mirrors are employed, the two eyes' views are fed to two separate matched displays. In each case, the testing methods discussed below are meant to help in identifying any existing differences in contrast, luminance, color, as well as any leakage or crosstalk from one eye's view into the other eye's view which produces ghost images). For example, if you put a white image into the left eye and a black image into the right eye and view them alternately by closing one and then the other eye in succession, you can find out how much one eye's view is leaking into the other eye. The patterns are shown in the figures below. Each figure has the separate left- eye and right-eye portions (on the left and right sides) though they are shown without spacing. The set of patterns is available as bitmap images at <https://doi.org/10.55410/Igam8989>.

Visual inspection using the patterns discussed above (or similar patterns of your choice) is highly recommended before conducting rigorous measurements. Visual inspection can easily identify a number of mis-alignment issues: loss of signal to a channel, faulty color driving, or similar problems before spending time on testing. Note: A small percentage of the population does not see the stereo effect and should check their vision to be aware of this.

17.6.1.1 PATTERNS FOR ALIGNMENT AND MAGNIFICATION

Before doing extensive testing, these patterns are for alignment of the two channels (both eyes), for checking that the magnifications are the same, and for making sure that the left and right eyes are properly oriented. Misalignment between the grid lines should be corrected until they overlap to the resolution of the display system, or the visual acuity of the viewer. It is especially important to align the horizontal lines (vertical orientation alignment). Alignment should be corrected by the display provider or the tester before testing. The square labeled LEFT should be visible in your left eye, and so on. If this is not the case, you should check the system for proper cabling or set-up installation.

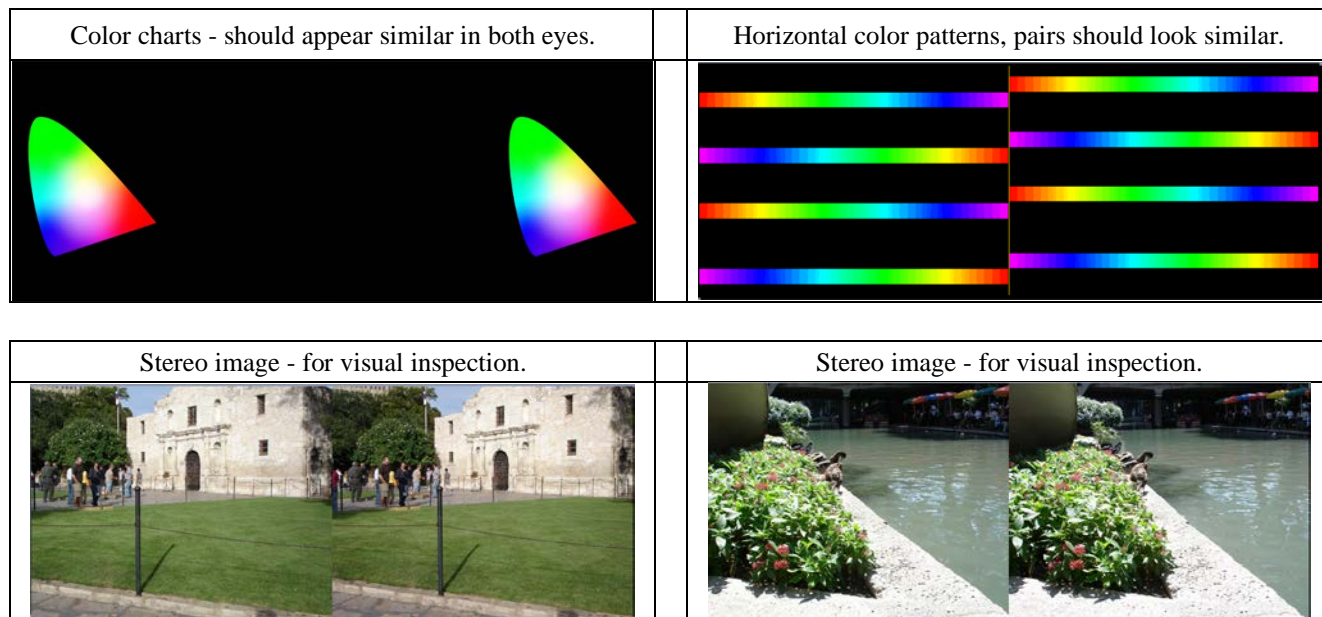
GRID - Grid pattern on both eyes - for checking alignment and magnification.	SQUARES - Square and horizontal lines on both eyes - for alignment.
	

Rectangles with notation should help identify that left square is viewed by left eye.	
	
LEFT EYE	RIGHT EYE

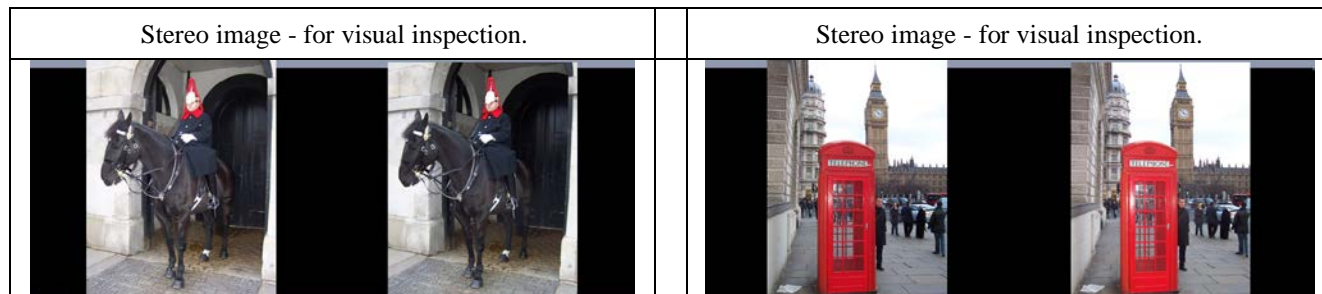


17.6.1.2 PATTERNS FOR VISUAL INSPECTION

These are the color patterns that help to check that all color codes and connections are proper, and there are no optical effects that shift the colors significantly. In both charts you should see the left and right sides, and the horizontal color bars should appear similar. There should be no depth effect (i.e. no binocular disparity) in these charts. Additional photos can be used in visual inspection of the stereo system. A blurry edge may be indicative of the existence of significant crosstalk (ghost image) in the system.



In the following, look for crosstalk (ghosting) along the high-contrast edges.

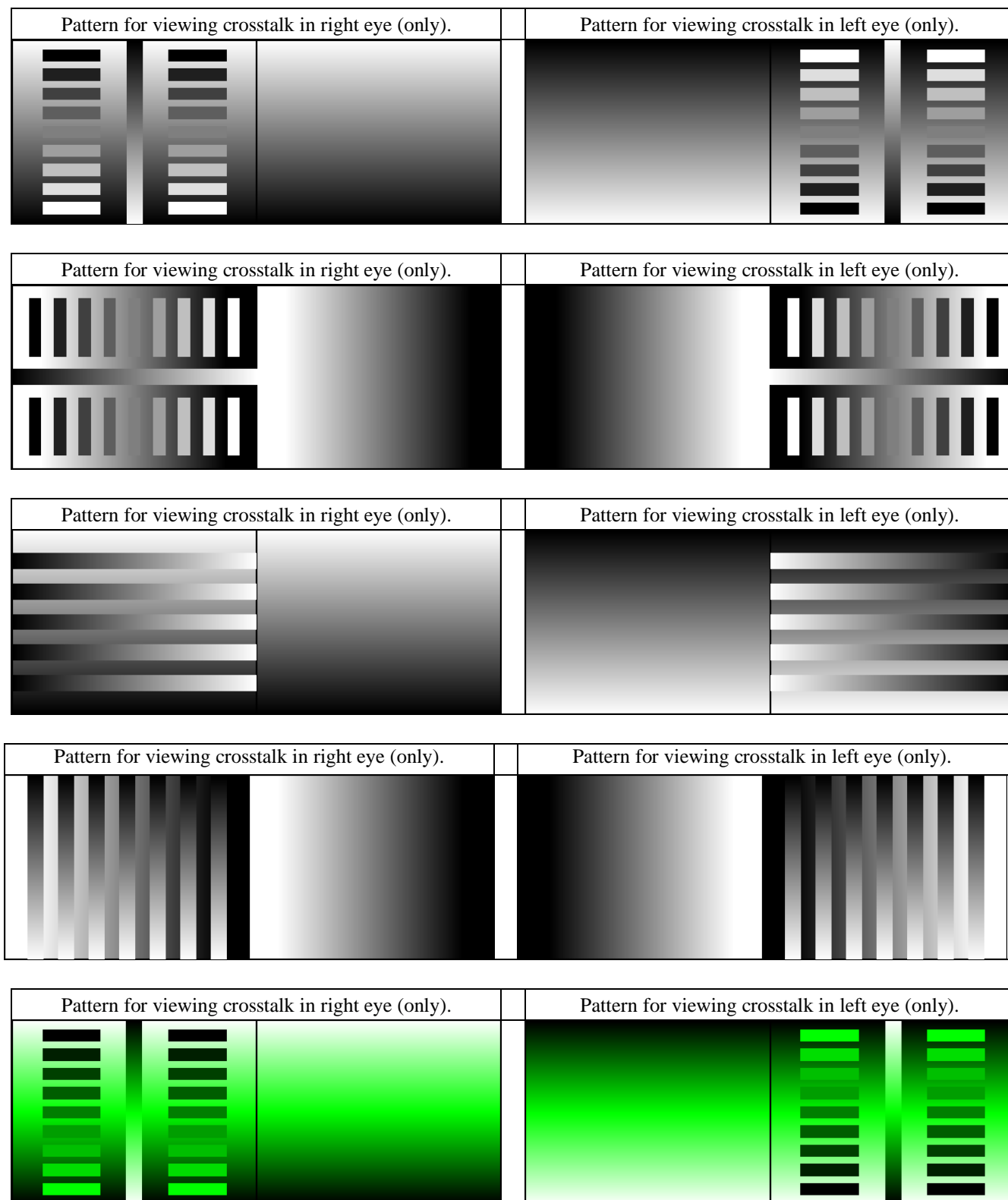




17.6.1.3 PATTERNS FOR VISUAL INSPECTION OF CROSSTALK

These patterns are not intended to be viewed simultaneously with both eyes at the same time to avoid binocular rivalry. Use only the one eye that looks at the plain gradient without the bars. Crosstalk problems will be indicated if faint images of the bars can be seen against the plain gradient. In a similar way, crosstalk sensitivity to head tilt and head location can be demonstrated.

3D & STEREOSCOPIC



Similar for red and blue.

3D & STEREOSCOPIC



17.6.2 PATTERNS FOR MEASUREMENT

The following patterns are useful for stereo contrast, crosstalk (ghost image), and luminance and color measurements. The patterns with differing left-right eye colors are not intended to be viewed simultaneously otherwise binocular rivalry will occur.

3D & STEREOSCOPIC

3D & STEREOSCOPIC

White / White – pattern (W/W).		Black / Black – pattern (K/K).	
Black / White – patterns (K/W).		White / Black – pattern (W/K).	
Red / Black – pattern (R/K).		Black / Red – pattern (K/R).	
Green / Black – pattern (G/K).		Black / Green – pattern (K/G).	
Blue / Black – pattern (B/K).		Black / Blue – pattern (K/B).	



17.6.3 PATTERNS FOR LIGHT-FIELD DISPLAYS

While all stereo patterns in 17.6.1 and 17.6.2 (except the photos for visual inspection) included a pair of left/right images rendering the stereo image at the display *surface*, we need images with *depth* for light-field displays. As explained in 17.5, each eye receives the light rays from different depths. Therefore, the following new image field notation will be used:

- (1) $FQ_{\pm x}$ = Full field for color $Q: \{R, G, B, W, K\}$, or combinations of mid gray levels (see Fig. 3 below), at depth x (mm), relative to the display surface ($x = 0$, $x > 0$ behind the display surface). Fields with combinations of mid-gray levels are denoted $F_{R,G,B,x}$, where R , G , and B denotes each input command level, respectively.



Fig. 1. Full-field uniform primary colors, white, and black, at depth $\pm x$ mm

- (2) Grid patterns.
- Grid patterns with $1/6$ height/width divisions are used for assisting the operator when focusing the photometer or camera, as well as for visually inspecting the system linearity.
 - Similarly to the full-field patterns, the grids can have any color and any depth, and are denoted $G_{f,b,x}$, where f and b are the fore- and background colors, respectively, $f, b: \{R, G, B, W, K\}$ and $G_{f_R:f_G:f_B,b_R:b_G:b_B,x}$ for combinations of mid-gray levels; $f_R, f_G, f_B, b_R, b_G, b_B: \{1, 2, 3 \dots 2^N - 2\}$, where N is the bit depth.
 - Figure 2 shows examples of grid patterns with black lines on white background ($G_{K,W,x}$) and white lines on black background ($G_{W,K,x}$).

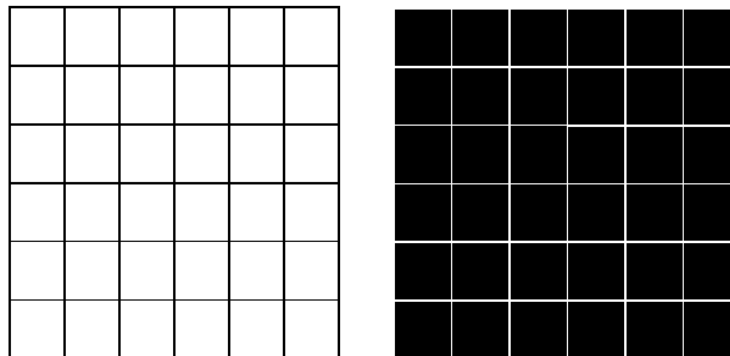


Fig. 2. Grid line patterns with black on white (K/W) and white on black (W/K) at a given depth x .



- (3) Gray levels are also defined at a given depth:

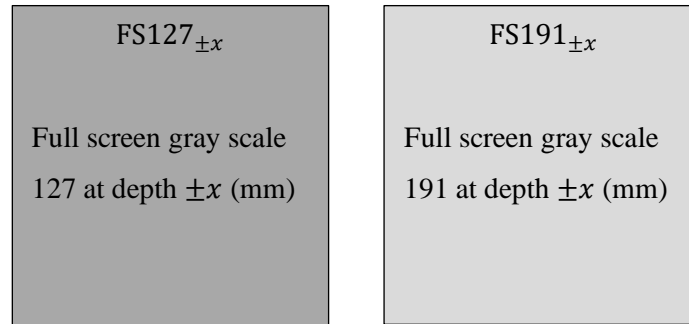


Fig. 3. Full screen gray scale patterns (left) $FS_{127,127,127,x}$, (right) $FS_{191,191,191,x}$ at a given depth x

- (4) Combination of several gray values and depths: Each square could be at a different depth, which makes this a very powerful pattern.



Fig. 4. Example of a test image with sub-patches, each with different combinations of mid-gray values and depths.

- (5) Resolution bars at a given depth:

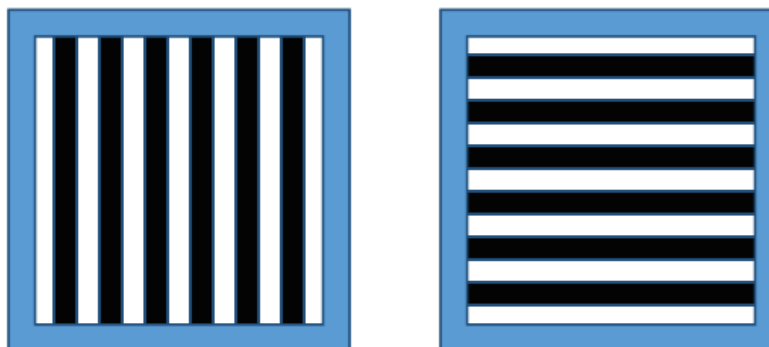


Fig. 5. Resolution bars at a given depth x . Note that the white and black bars have the same depth.



(6) Resolution Patterns (Sinusoidal):



Fig. 6. Resolution patterns at a given depth x with sinusoidally varying gray levels. Note all grey levels have the same depth

(7) Checkerboard patterns

This pattern is a special case of (4). White and black can have different depths and the pattern is denoted $CBpW \pm x_K \pm y$, where x_K and y is the depth in mm of black and white, respectively, and p^2 is the number of sub-squares.

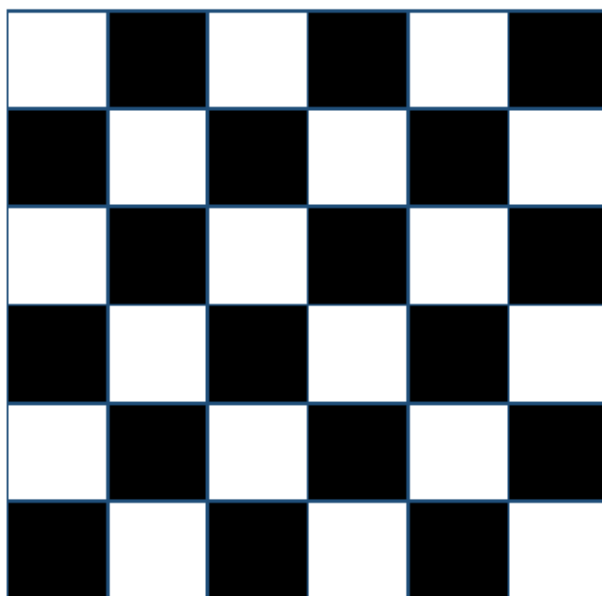


Fig. 7. Example of a checkerboard pattern “CB6W10K-10” with $6 \times 6 = 36$ squares where white and black squares have the depths 10 and -10 mm, respectively.



17.6.4 PATTERNS FOR VISUAL INSPECTION OF LIGHT-FIELD DISPLAYS

As mentioned, light-field displays, volumetric and holographic displays need images with depth. For visual inspection, a rotating hedgehog pattern was proposed (see references [13] and [15] in 17.5):

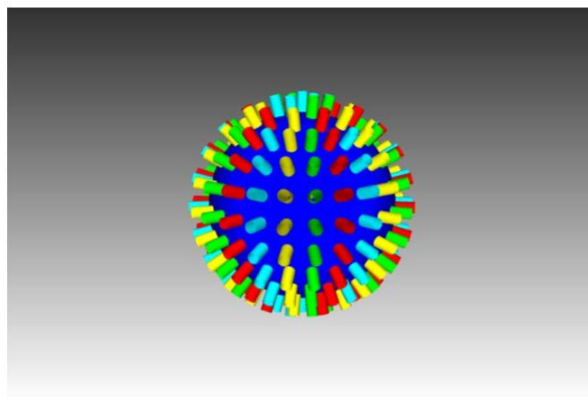


Fig. 8. Rotating hedgehog pattern with total depth about $\frac{1}{2}$ the height of the object. Center of gravity depth is at the display surface. For a light field display with lenslets, the gravity is above the lenslets sheet surface. A video with 1° steps (360 frames) is available in the IDMS test pattern directory.

Vendors supplied still/moving images:

1. Many display systems will be accompanied by typical demonstration images
2. Display these images and look for any irregularities
3. If there is a problem, check the system. Otherwise, proceed with the measurements



18. TOUCH SCREEN AND SURFACE DISPLAY

The following tests can be used to verify the functionality and performance common to most touch screen display technologies using either a finger or stylus inputs. Note: many of the suggested tests are new and under development. The touch screen and surface display technology is evolving, and these tests will become more refined and reproducible as it continues to grow. Specific tests for each type of touch technology will not be covered at this time but may be added to future versions.

PLEASE NOTE: Some of the tests and visualization techniques presented in this chapter are suggested methods that are under development. They are intended to be performed on a touch screen display when initially acquired from the manufacture. Repeatability and reliability testing over time will not be included. If the display manufacture suggests that a protective film be used, the device should be tested with and without the film (if possible) to determine its performance in either case.

APPLICATION: Most of the tests described in the following sections can be used on all types of touch screen and surface displays. Some tests may be better suited for specific types and others may not apply to a specific type or technology. Typical types of touch screen displays that can utilize these methods are capacitive, resistive, infrared, surface acoustic wave (SAW), and vision based surface displays. A brief description of some of the basic types of displays is given below. A good source for more information on these and other technologies can be found in the Touchscreen Tutorial.¹

- **Capacitive-** These displays consist of an insulator coated with a transparent conductor such as ITO. Since the human body is a good conductor, a touch will be recognized as a distortion in the electrostatic field of the screen and can be measured as a change in capacitance.
Positives: Durable, greater optical transmittance, highly sensitive to touch and drag, not affected by surface contaminants.
Negatives: Only fingers or conductive stylus input, susceptible to EMI, environmental changes affect performance, requires periodic calibration.
- **Resistive-** These displays can be composed of several layers but the touch reaction comes from interaction of two electrically conductive layers (usually separated by a narrow gap). When the two layers come in contact, the panel acts like a voltage divider and the location of the touch event can be determined.
Positives: Comes in various sizes, can be activated by any type of device, water-proof, and low power consumption.
Negatives: Durability, poor transmittance and optical qualities due to multiple layers, requires periodic recalibration.
- **Infrared-** These displays utilize an array of Infrared LED's and photodetector pairs around the edge of the screen. When a touch even occurs, the disruption of the X-Y pattern created by the LED beams indicates the location of the touch.
Positives: Detects most any input: finger, gloved finger, stylus or pen, does not require patterning on the glass, highly transmissive and durable.
Negatives: Low resolution higher cost than other technologies. Bezel can be big and bulky.
- **Surface Acoustic Wave (SAW) -** These displays use ultrasonic waves that pass over the touchscreen panel. When a touch event occurs, a portion of the acoustic wave is absorbed. In this way a touch location can be detected.
Positives: Available in large sizes up to 60", highly transmissive and durable, inputs include finger, gloved hand, and soft stylus, vandal resistant.
Negatives: Can be damaged by outside elements. Contaminants on the surface can interfere with its functionality.
- **Vision Based (Surface).** These displays use two or more image sensors placed strategically either near the edge or beneath the surface of the display. Infrared lighting illuminates the touch surface, and a touch reaction can be seen as either a shadow or reflection off an object.
Positives: Can be activated by any input device even objects, highly transmissive and durable, accurate multi-touch functionality, can recognize objects above the surface.
Negatives: Not available in small sizes, big and bulky, false touch events can be triggered by ambient lighting containing IR.

Many other types or varieties of these basic technologies are evolving and maybe be included in future versions of the IDMS.

¹SID 2007 Display Applications Conference – Touchscreen Session by Geoff Walker (Principal Consultant, Walker Mobile), Frank Lung (Product Manager, Elo TouchSystems), James Roney (Manager of Touchscreen Development, Elo TouchSystems), Ken Miller (Global Technical Service Manager, 3M Touch Systems), Bruce DeVisser (Product Marketing Manager, Fujitsu Components)



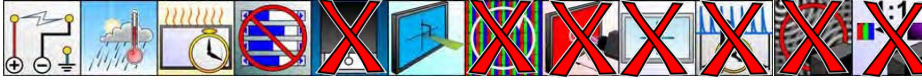


18.1 TOUCH FUNCTIONALITY

ALIAS: touch accuracy, linear accuracy.

DESCRIPTION: Touch displays should be tested for basic functionality such as touch events and movement. The touch tests described in this section test the touch accuracy and linear accuracy of most touch or surface display.

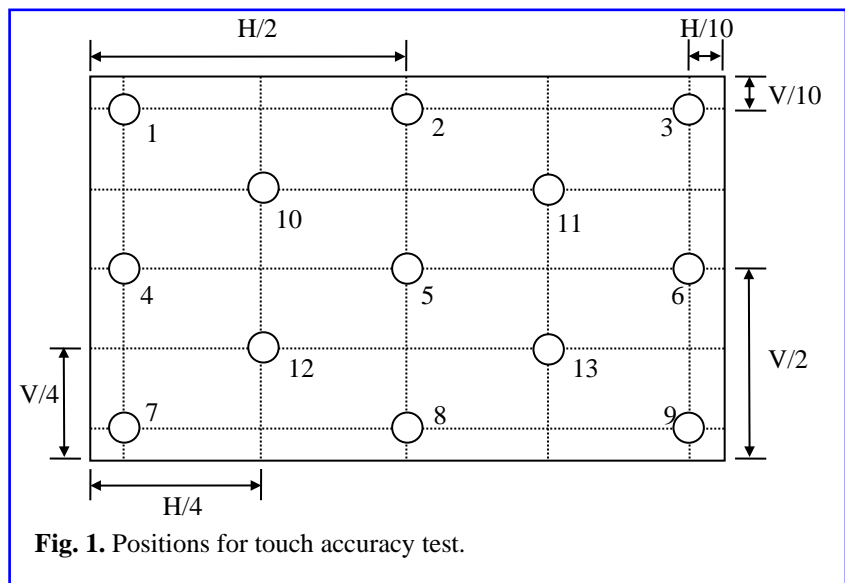
SETUP: The following icons indicate the basic test conditions for the following tests.



OTHER SETUP CONDITIONS: Access to digitized output or Human Interface Device (HID) through appropriate software to determine the location of the touch event or custom software for input location recognition. The complete system response should include the computer digitization as well as the touch device response time. Accuracy can be improved with the use of automated test equipment such as robotics. Custom templates can be designed for touch displays with pen or stylus inputs. For automated testing, a specific diameter rubber column (~ 6 or 8 mm diameter), or copper plug can be used for repeatable input.

18.1.1 TOUCH POSITION ACCURACY

PROCEDURE:



1. Touch Accuracy

The digitized output of the device under test (DUT) should read the x, y coordinate of the test touch positions. An example is shown in Figure 1. The touch test positions should be in the center and at equal distances from the edge of the display. If software exists from the manufacture that will display the location of the touch event for the DUT, it can be used to determine if the location of the touch event is accurate. An example is shown in Figure 2. If automated test equipment is used, the location of the test object should be known and can be compared to the digitizer output.

2. Correct Response to Input



The test can be a visual observation or automated, which should give a more precise repeatable test result. The automated test equipment should use the typical tapping material, force, and area for the DUT. An example tapping material is rubber or copper. When using rubber, the hardness should be recorded as it can affect the touch response. Using copper can be a more durable choice. The touch position should be shown as a circle the size of the diameter of the test tool. The tapping force should be from 50 to 500gw (gram weight). Typical finger touch is in the range of 200 to 400gw.

3. Multi-touch Response (if applicable)

If the touch screen display is a multi-touch display, then the functionality should be tested for more than one touch point at a time. Multiple test positions can be used at the same time to determine if the DUT accurately reads both inputs. Other touch locations may need to be tested for functionality such as two points in a row or column to see if the DUT can determine touch events in these locations at the same time.

ANALYSIS: The accuracy of the DUT should be tabulated in a table and include the location specified and the measured location. A sample table from an automated test is shown below.

REPORTING: The accuracy of the touch display may depend on the type of input device used. The accuracy may vary with different inputs. The report should contain testing parameters, any automated test equipment settings, and specified and measured coordinates. The touch panel information should also be included in the report. Other observations such as gesture recognition and multi-touch functionality should be included as well.

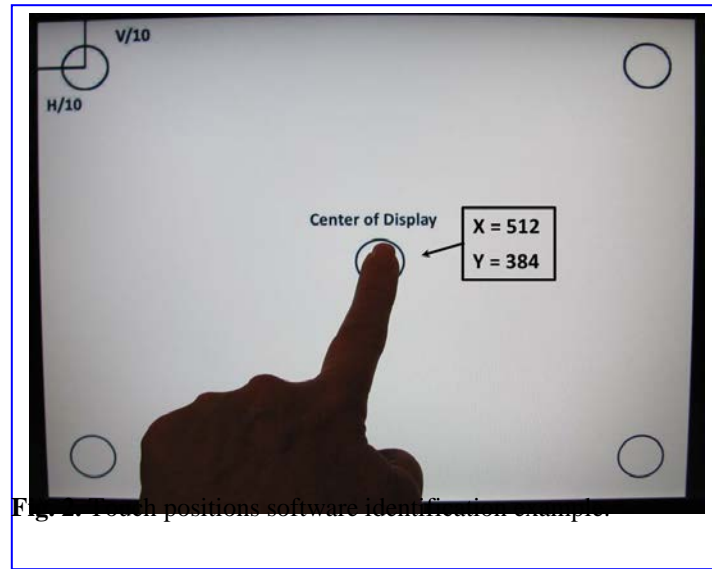


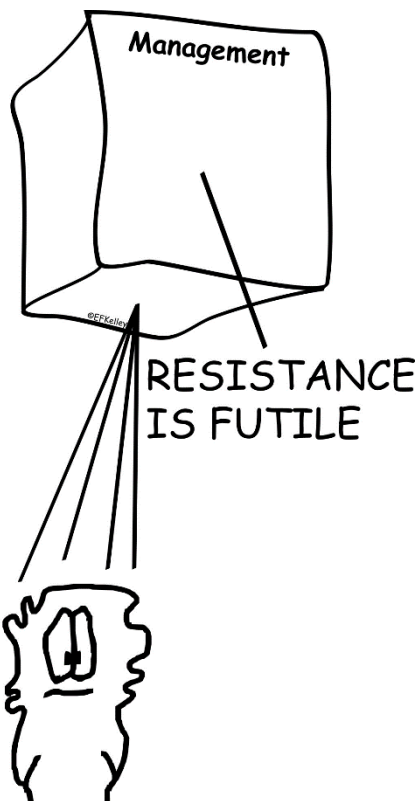
Figure 18-1 Touch positions software identification example.

—SAMPLE DATA ONLY—

Values shown here are for illustration purposes only; they do not suggest expected measurement results.

Reporting Example

Material		Copper
Diameter		8mm
Force		250gw
Specified Coordinates (x,y)		Measured Coordinates (x,y)
Position #1	(X1, Y1)	(X1', Y1')
Position #2	(X2, Y2)	(X2', Y2')
Position #3	(X3, Y3)	(X3', Y3')
Position #4	(X4, Y4)	(X4', Y4')
Position #5	(X5, Y5)	(X5', Y5')
Position #6	(X6, Y6)	(X6', Y6')
Position #7	(X7, Y7)	(X7', Y7')
Position #8	(X8, Y8)	(X8', Y8')
Position #9	(X9, Y9)	(X9', Y9')
Position #10	(X10, Y10)	(X10', Y10')
Position #11	(X11, Y11)	(X11', Y11')
Position #12	(X12, Y12)	(X12', Y12')
Position #13	(X13, Y13)	(X13', Y13')



Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



18.1.2 LINEAR ACCURACY

PROCEDURE: The digitizer output of the device under test (DUT) should read the x, y coordinate of several lines. An example of test lines and their input response is shown in Fig. 3. The software should be able to record the coordinates of the line drawn by the input device at a specified speed.

ANALYSIS: Different input devices will result in different linear accuracy. A typical motion can range from 30 to 200 mm/sec. The lines drawn should extend over the entire display unless there is an edge as shown in Fig. 4. The red line shown in Fig. 5 is plotted by linking to the reporting positions. The red and blue lines can be characterized by determining the maximum and averaged differences as defined below. To recognize the parallel shift of the reported line, a trend line with the same slope as the specified line can be used (see Fig. 6). A minimum root-mean-square method can be used to determine the distance from the reporting points and the trend line, the tendency line. The distance difference of the two lines is defined as average difference.

Maximum difference: the maximum distance from the reported point (red line) to the specified line (blue line).

Averaged difference: the distance between the averaged red line and the specified line (blue line).

REPORTING: The report should contain testing parameters, any automated test equipment settings, the specified and measured line coordinates, and the maximum and average differences. The touch panel information should also be included in the report.

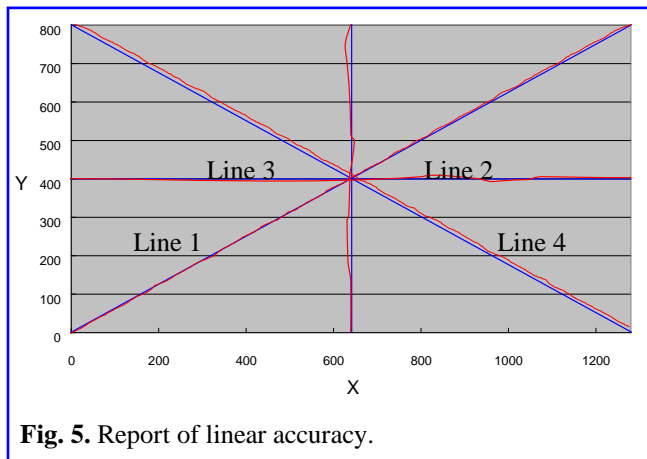


Fig. 5. Report of linear accuracy.

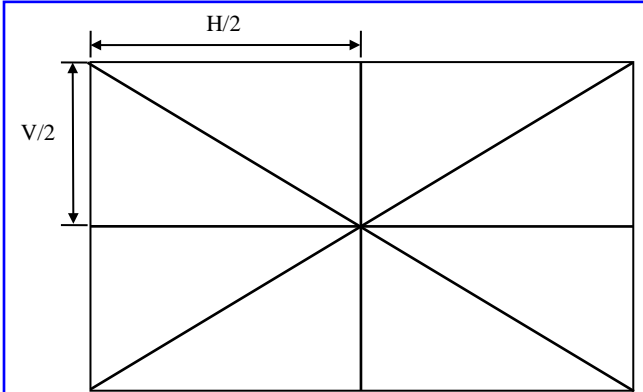


Fig. 3. Positions for linear accuracy test.

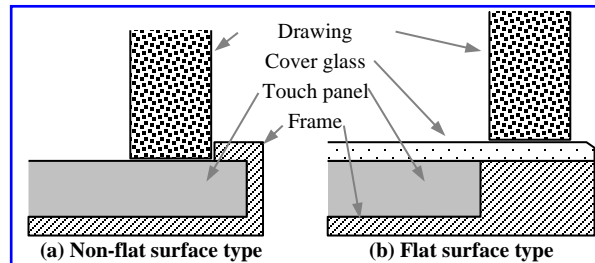


Fig. 4. Cross sectional positions for linear accuracy test.

—SAMPLE DATA ONLY—		
Reporting Example		
Material	Copper	
Diameter	8mm	
Force	250gw	
Speed	70mm/sec	
Specified Line	Maximum Difference	Average Difference
Line 1		
Line 2		
Line 3		
Line 4		

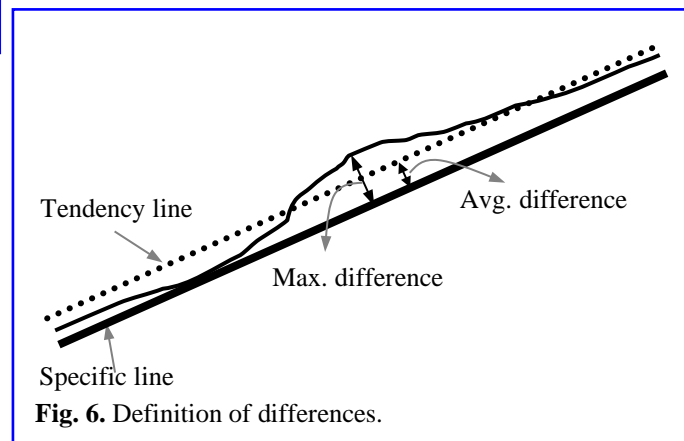


Fig. 6. Definition of differences.



18.2 REACTION TIMES

ALIAS: latency, lag time.

DESCRIPTION: Touch displays should react to the user input in a reasonable time. The average user will usually notice latencies or lag time between touch and reaction if the total system reaction time is much greater than 100 ms. Certain gestures should have even lower reaction times for optimum response. The tests described in this section are under development and there may be other more accurate methods for individual touch screen and surface display technologies available. Most of these require custom software usually supplied by the manufacture or available through third parties.

SETUP: The following icons indicate the test basic test conditions for the following tests.



OTHER SETUP CONDITIONS: Access to digitized output or Human Interface Device (HID) through appropriate software to determine the reaction time of a touch input. The alternatively method described in this section is not the most accurate but is a simple quick test that can be done without the aid of expensive equipment such as a robot, or custom software. A machine vision camera or video recorder with a fast frame rate of at least 30 fps can be used to determine the reaction time and latency of the DUT. Custom templates can be designed for touch displays with pen or stylus inputs.

COMMENT: Several types of reaction times are described in the following subsections.

18.2.1 REACTION TIME: LATENCY OF A SINGLE TOUCH

PROCEDURE: If the digitized output can be read, then it can be used to determine the latency t_{STR} of a single touch. The total time between touch activation and display response should be measured, not just the response of the touch device itself. Record a touch sequence and determine the time t_{STR} between the actual touch and the final reaction of the display to that touch. If the digitizer output is not available, then a machine vision camera with a zoom or close up lens or video recorder can be used to grab a sequence of images during a touch event. The response time can then be determined from the images but only within the limits of the frame rate f of the detection device. For example, a $f = 30$ fps cameras will have a

capture rate of $\Delta t_c = 1/f = 33.3$ ms per

frame so the resultant response time will be limited to a multiple of this interval. The images in Figure 7 were obtained with a video camera with a frame rate of 30 fps. Video can be converted to individual frames using many common software tools. The camera should either use a zoom lens or be positioned such that the frame which activates the touch, and the touch response can be easily separated from the capture of multiple frames. This technique is not the most accurate method and can be off by 1 frame due to interpretation of the observer.

COMMENT: Many new tools are in development for specific types of touch technologies which should lead to more accurate and repeatable results. The need for a standard activation device is evident and are under development, but each technology will most likely need to be tested with the most common input device, be it a finger, a stylus, or conductive device. Automated test fixtures such as robots would also increase the accuracy and repeatability, but this equipment can be expensive and sometimes difficult to use.

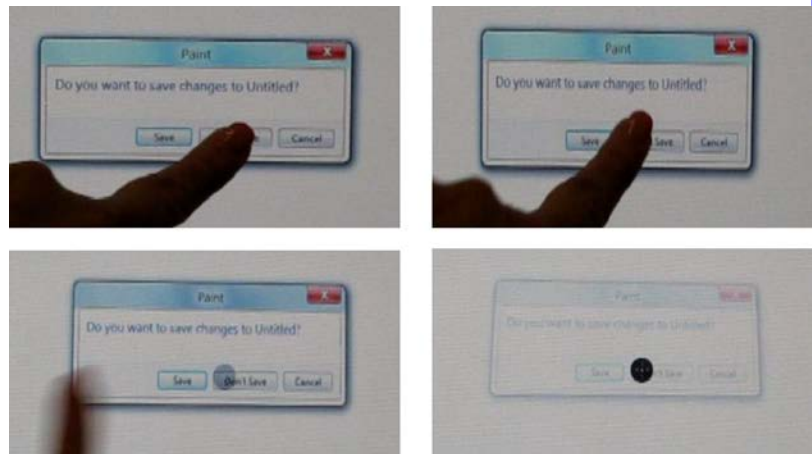


Figure 7. Captured images of a touch event (1 frame separation).



ANALYSIS: The latency of a single touch response can be calculated by studying the images collected in the sequence and determining the number of frames between when the touch occurred and when the reaction was observed. This measurement is limited to a multiple of the frame rate of the technique used to record the sequence. Count the number Δn frames from touch to reaction and divide by the frame rate f to calculate the latency of a single touch or single-touch response time t_{STR} :

$$t_{STR} = \frac{\Delta n}{f} \quad (1)$$

REPORTING: Report the touch frame number, the reaction frame number, the number of frames from touch to reaction, the frame rate, and the response time.

—SAMPLE DATA ONLY— Values shown here are for illustration purposes only; they do not suggest expected measurement results.	
Reporting Example	
Touch Frame #	15
Reaction Frame #	17
# of Frames, Δn	2
Frame Rate, f	30 fps
Response Time, t_{STR}	60 ms

18.2.2 REACTION TIME: LATENCY OF A LATERAL MOTION

PROCEDURE: If the digitized output can be read, then it can be used to determine the latency of a lateral motion. A Paint program can be used if available on the DUT to record a typical motion sequence and determine the lag time (latency) between the input and the system reaction. If the digitizer output is not available, then a machine vision camera with a zoom or close up lens or video recorder can be used to grab a sequence of images during the lateral motion as described in § 18.2.1. A typical lateral motion that does not track well is shown in Figure 8.

ANALYSIS: The latency of a lateral motion can be calculated by studying the images collected in the sequence and determining the distance between the touch position and the object being moved and the velocity of the movement. This measurement is limited to a multiple of the frame rate of the technique used to record the sequence. A video camera with a frame rate of 30 fps was used to record the sequence shown in Figure 4.

Measure the distance between the touch position and the object, d_{fo} and the distance moved, d_{mov} by either determining the mm/pixel conversion or simply placing a measuring device next to the motion displayed and determine the distance from the scale on the measuring device. Calculate the motion velocity, V_M to obtain the lag time, t_L using the following equation.

$$V_M = \frac{d_{mov}}{f \Delta n} \quad (2)$$

$$t_L = \frac{d_{fo}}{V_M} \quad (3)$$

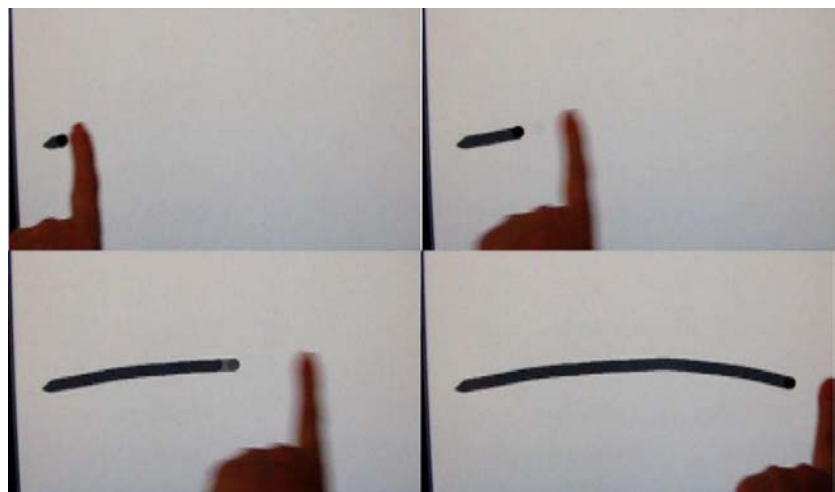


Figure 8. Captured images of a lateral motion (10 frames separation).

—SAMPLE DATA ONLY— Values shown here are for illustration purposes only; they do not suggest expected measurement results.	
Reporting Example	
Distance Between, d_{mov}	90 mm
Distance Finger to Object, d_{fo}	50 mm
Frame Rate, f	30 fps
Motion Velocity V_M	60 mm/s
Lag Time t_L	833 ms



18.2.3 REACTION TIME: FASTEST MOVEMENT RECOGNIZED

PROCEDURE: If the digitized output can be read, then it can be used to determine the fastest detectable motion of the DUT. Record a touch sequence at the fastest typical motion for the DUT and determine the time between the initial touch and the final release of a lateral motion such as a “swipe” or a “flick”. Measure the distance moved in order to calculate the fastest movement recognized. The reaction to the touch motion should stay within a reasonable distance from the input device in order for it to be considered tracking well. It may take a few iterations to determine the best (fastest) motion for the particular DUT. If the digitizer output is not available, then a machine vision camera with a zoom or close up lens or video recorder can be used to grab a sequence of images during the lateral motion as described in § 18.2.1. An example of a tracking movement that does not track well is shown in Figure 9.

ANALYSIS: The latency of a lateral motion can be calculated by studying the images collected in the sequence and determining the number of frames Δn needed to move an object a specified distance without significant lag. Note: the motion must keep the object within a reasonable distance from the touch device. Determine the maximum movement velocity without noticeable lag. This measurement is limited to a multiple of the frame rate f of the technique used to record the sequence. A video camera was used to record the sequence shown in Figure 5 which had a frame rate of 30 fps.

Determine the number of frames Δn required to move an object a specified distance, d . Calculate the maximum lateral motion without lag, maximum movement velocity V_{MM} .

$$V_{MM} = \frac{fd}{\Delta n} \quad (4)$$

REPORTING: Report the number of frames, distance moved, frame rate, and the maximum movement velocity in mm/s.

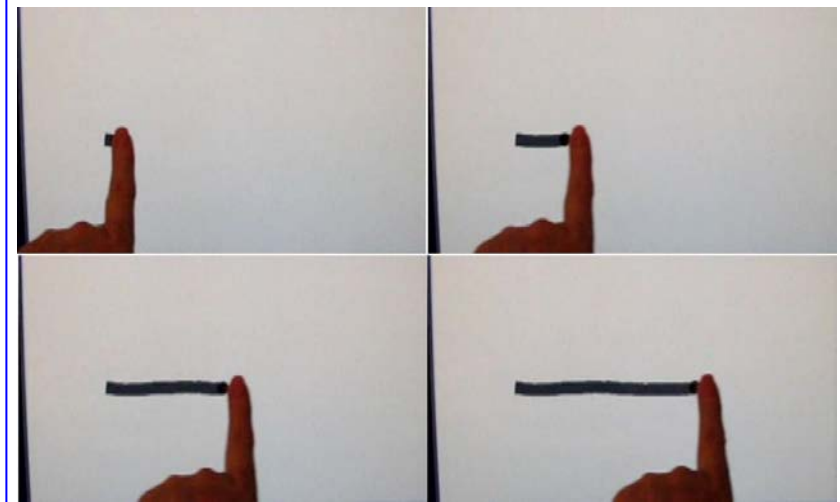


Figure 9. Captured images of a lateral motion (10 frames separation).

—SAMPLE DATA ONLY—	
Values shown here are for illustration purposes only; they do not suggest expected measurement results.	
Reporting Example	
# of Frames, Δn	10
Distance, d	40 mm
Frame Rate, f	30 fps
Maximum Movement Velocity V_{MM}	120 mm/s



18.3 AMBIENT DEGRADATION

DESCRIPTION: The ambient degradation of a touch screen or surface display can be determined by utilizing the test methods described in § 11.9 Ambient Contrast. However, most touch displays are used at some angle of incidence so the angular contrast ratio should be measured as close to the angle that the DUT is typically designed for. Many touchscreen and surface displays are intended to be used in many different ambient lighting scenarios, so the DUT should be tested in the range of ambient conditions for which it will most typically be used. If the touch display is used with a protective film, the test described in this section should be done with and without the protective film if possible.

SETUP: The following icons indicate the basic test conditions for the following tests.



OTHER SETUP CONDITIONS: The setup description in § 11.9 can be used to measure the ambient contrast at the typical viewing angle for the DUT. For text readability and image content degradation, an array detector is placed at the typical viewing angle and a diffuse source is used to illuminate the DUT at the normal expected illuminance conditions. The source used to illuminate the DUT should have the capability to produce all lighting scenarios that the DUT might experience. A list of typical ambient lighting conditions is shown in § 11.9, Table 1. A hemispherical illumination with specular excluded will be used for testing the text readability and image content degradation (see § 11.2 for hemispherical setup). The measurement should take into account veiling glare contributions that often corrupt the result (see the appendix A2 Stray-Light Management and Veiling Glare and A2.2 Accounting for Glare in Small-Area Measurements).

COMMENT: Three types of ambient degradation are described in the following subsections.

PROCEDURE:

1. Ambient Contrast Degradation

For the touch screen or surface display, determine the angles most likely to be used and the typical lighting condition. Note: some touch screen and surface displays are viewed at more than one angle and in more than one environment. The ambient contrast for each typical usage scenario should be measured and recorded using the method described in § 11.9 Ambient Contrast.

2. Text Readability Degradation

At the same angles and lighting conditions used previously, use the method described in § 7.8 Resolution from Contrast Modulation, to determine the line resolution for which the Michelson contrast is equal to 50%. This is recommended for good text readability and helps determine the minimum font size that can be displayed without degradation. A modified procedure for measuring the $n \times n$ grille patterns can be done by using an array detector such as a machine vision camera that has been flat field corrected. Use a high-quality zoom lens with a field of view that measures at a minimum of 10 LOLO pairs at the lowest resolution (1 line on/ 1 line off).

3. Image Content Degradation

At the same angles and lighting conditions used previously, use the method described in § 7.8 Resolution from Contrast Modulation, to determine the line resolution for which the Michelson Contrast is equal to 25%. This is recommended for good image visibility with sharp edges and good contrast.

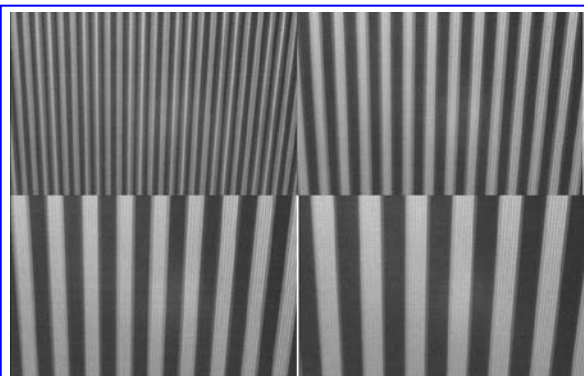


Figure 10. Line On/Line Off patterns displayed on the DUT in a typical ambient environment (in this case ~ 250 Lux) at a typical viewing angle (in this case 45°).

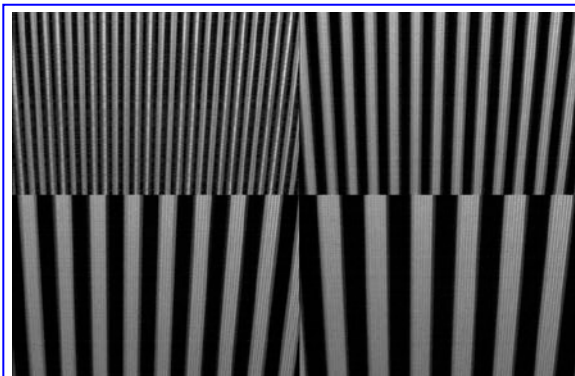


Figure 11. Line On/Line Off patterns displayed on the DUT in a dark environment at a typical viewing angle (in this case 45°).

ANALYSIS:

1. The calculation of the ambient contrast described in § 11.9 Ambient Contrast should be done for each angle and illuminance tested.
2. The images shown in Figures 10 and 11 are 1 x 1, 2 x 2, 3 x 3, and 4 x 4 grille pattern displayed at a typical viewing angle in the dark and at a typical ambient condition. The ambient Michelson contrast C_{MA} is calculated using image analysis software by determining the average max and average min of 10 neighboring line profiles. The C_{MA} is calculated for each grille pattern and each lighting condition. Using the techniques described in § 7.8 Resolution from Contrast Modulation, plot the C_{MA} for each grille pattern, angle, and lighting condition and determine the n_{text} where the contrast drops to 50%. This will indicate the text font size that can be easily recognized at the angle and ambient environment tested.
3. Using the data collected in § 18.2, determine n_{image} (where the contrast drops to 25%) for each angle and lighting scenario tested.

REPORTING:

1. Report all the measured and calculated values used to determine the C_{MA} for each angle and lighting scenario tested.
2. Show n_{text} and n_{image} on a graph of the C_{MA} vs. Grille Line Width (LOLO pattern) as shown in Figure 12.

—SAMPLE DATA ONLY—												
Values shown here are for illustration purposes only; they do not suggest expected measurement results.												
Reporting Example												
Grille Pattern	1 x 1			2 x 2			3 x 3			4 x 4		
	Min	Max	C_{MA}	Min	Max	C_{MA}	Min	Max	C_{MA}	Min	Max	C_{MA}
Dark Environment, 45°	123	32	59%	107	8.2	86%	84	8.6	81%	67	7.6	80%
Ambient Environment 250 Lux, 45°	100	54	30%	104	48	37%	92	76	9%	91	81	6%



18.4 SURFACE CONTAMINATION EFFECTS

ALIAS: fingerprints, smudges, permanent cleaning damage.

DESCRIPTION: Touch displays are very susceptible to fingerprints, smudges, and the damage due to cleaning. They must be very durable and able to maintain functionality and good display qualities even after thousands of touch events. Some touch displays claim to have fingerprint resistant coatings which should be evaluated for degradation of the touch functionality and the display quality. The following techniques are under development and may change as industry gets better at protecting touch displays from damage or undesirable contamination.

SETUP: The following test basic test conditions tests.

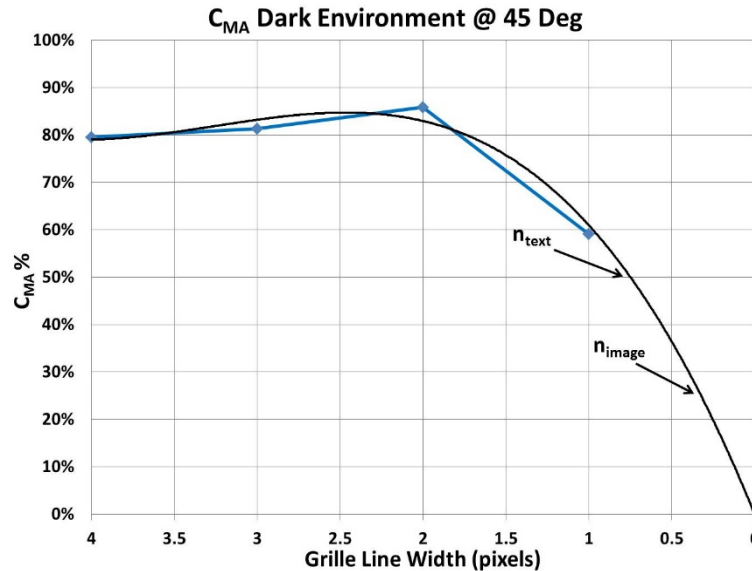
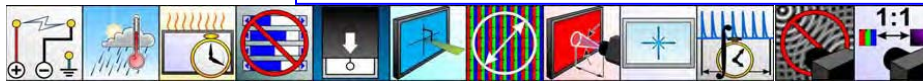


Figure 12. Extrapolation of C_m used to determine the 50% line width.



OTHER SETUP CONDITIONS: A suggested method that is under development uses the setup description in §11.9 to measure the ambient contrast at the typical viewing angle for the DUT with and without the presence of fingerprints or smudges. The area tested should include the contamination under evaluation.

PROCEDURE:

1. Fingerprint and Smudge Effects on Touch Functionality

There is no set procedure for creating a fingerprint or smudge on a touch screen or surface display. One method, described in this section, can be used to evaluate the touch functionality of the DUT. Using a basic hand lotion, create a fingerprint and smudge on the DUT at several test points on the display. The touch functionality positions in § 18.1 can be used for this test. An example of a fingerprint and smudge produced with this method is shown in Figure 13.

2. Fingerprint and Smudge Effects on Display Quality

Using the same technique described in § 18.1, create a fingerprint and smudge at the center of the display. Since most fingerprints and smudges are not apparent in dark room conditions, use an ambient lighting scenario which highlights the contamination. Using the method described in § 18.3, measure the degradation in contrast due to the fingerprint or smudge.

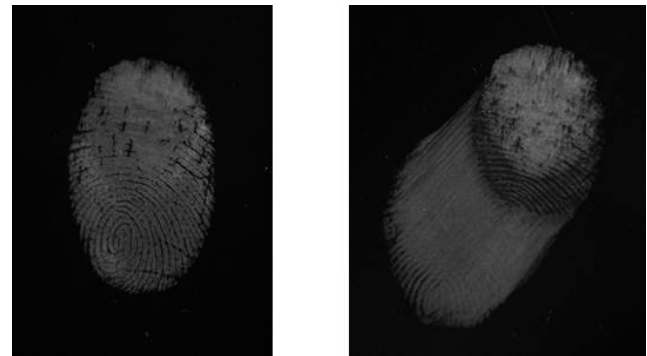
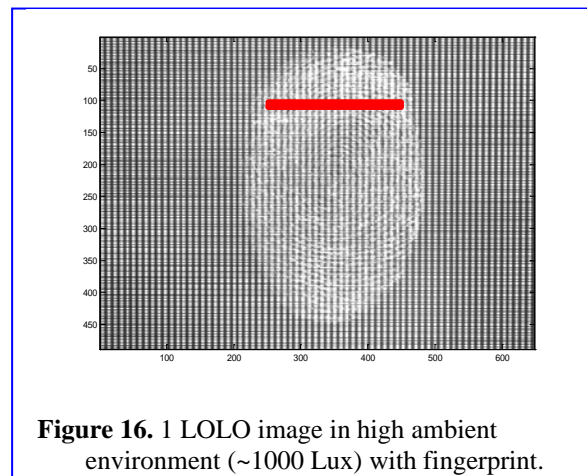
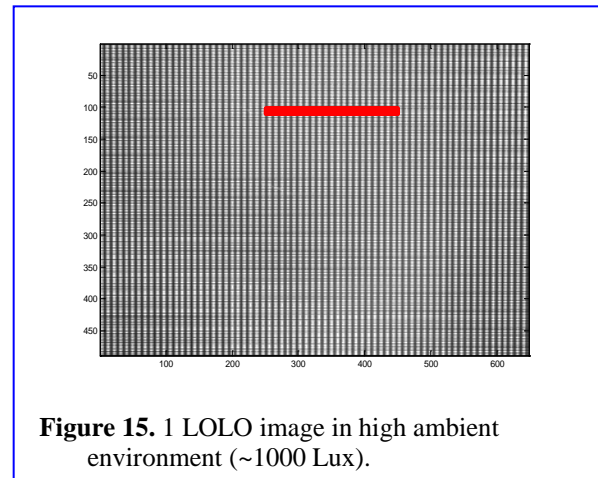
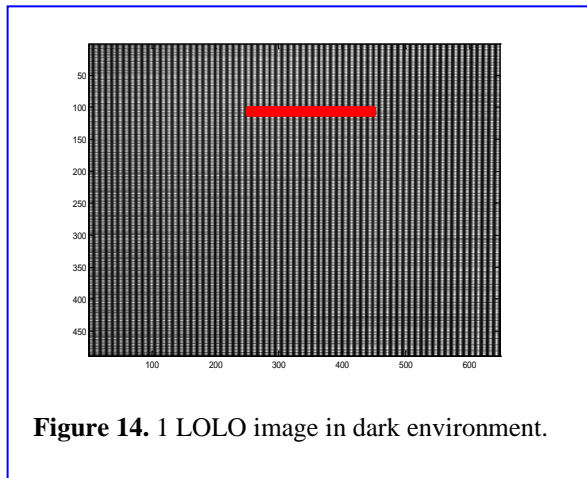


Figure 13. Fingerprint and smudge created with hand lotion coated finger.

**ANALYSIS:**

1. Repeatedly test the touch functionality (as described in § 18.1) of the DUT at the locations of the fingerprints and smudges.
2. Measure the contrast of the display with the fingerprint and smudge, then remove the contamination (following the manufactures recommended technique for cleaning the display) and re-measure the contrast at the same locations. One Line on/ Line Off images are shown in Figures 14 -16. Data was taken with a machine vision camera and zoom lens in a dark environment and under high ambient lighting (~ 1000 Lux) with and without a fingerprint. The red line shows the region where the data was analyzed using a mathematical program. The average the max and min of 10 consecutive line profiles was used to calculate the Michelson contrast C_M . Example calculated contrast degradation is shown in the Table below.

—SAMPLE DATA ONLY— Values shown here are for illustration purposes only; they do not suggest expected measurement results.			
Reporting Example			
Picture	Max	Min	C_m
1 LOLO Dark	193	26	.76
1 LOLO Ambient	224	92	.42
1 LOLO Ambient with Fingerprint	243	152	.23





REPORTING:

1. Report the locations of the test points, total number of touch events, number of touch events recognized, and number of touch events not recognized at each test location.
2. Report the change in contrast due to the contamination.

18.5 TEXTURE SURFACE TREATMENTS & PROTECTIVE FILMS

ALIAS: finger resistant, smudge proof, easy clean, protective film.

SETUP: The following icons indicate the test basic test conditions for the following tests.



OTHER SETUP CONDITIONS: The setup description in § 11.9 can be used to measure the ambient contrast at the typical viewing angle for the DUT as described in § 18.3. If possible, the display should be tested with and without the texture or protective film. An alternate method for determining the effects of the surface treatment or protective film is to measure the Distinctness of Image (DOI) using one of the three methods described in the ATSM standard test D5767-95 Standard Test Methods for Instrumental Measurement of Distinctness-of-Image Gloss of Coating Surfaces or a Gloss/Haze/DOI meter.

PROCEDURE:

1. Effects of Texture Surfaces or Protective Films on Touch Functionality

If the textured surface is not adhered to the surface of the display, test the DUT for touch functionality with and without the texturing or protective film as described in § 18.1. If the textured surfaced or protective film is not removable, the results can be compared to other similar displays without textured surfaces or protective films.

2. Effects of Texture Surfaces or Protective Films on Display Performance

If the textured surface is not adhered to the surface of the display, test the DUT for ambient contrast as described in § 18.3 with and without the texturing or protective film. If the textured surfaced or protective film is not removable, the results can be compared to other similar displays without textured surfaces or protective films. Alternatively, select one of the three methods described in the ATSM standard test procedure D5767-95 and measure the DOI for the display with and without (if possible) the surface treatment or protective film.

3. Cleaning Limitations and Restrictions

Most displays with textured surfaces or protective films will have special instructions for cleaning the surface without damaging it or degrading the display quality.

ANALYSIS:

1. Repeatedly test the touch functionality of the DUT with and without the textured surface or protective film (if possible). Record the number of touch events that are not recognized.
2. Measure the contrast of the display with and without the texture or protective film (if possible). Measure the DOI for the display with and without the texture or protective film.
3. Include any special instructions for cleaning or care for the display due to the textured surface or protective film. The recommended method for cleaning should be tried then the DUT retested for ambient contrast and/or DOI to determine whether the cleaning degraded the display quality.

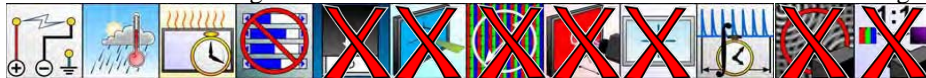
**REPORTING:**

1. Report the locations of the test points, total number of touch events, number of touch events recognized, and the number of touch events not recognized at each test location. Report the change in contrast due to the textured surface or protective film.
2. Report the change in contrast or DOI due to the textured surface or protective film.
3. Report the change in contrast or DOI due to the textured surface or protective film after cleaning the display using the manufactures designated cleaning procedure.

18.6 VISUAL OBSERVATIONS

ALIAS: matte finish, glossy, mirror like, speckle

SETUP: The following icons indicate the test basic test conditions for the following tests.



PROCEDURE:

1. Glossy or Matte Finish

There are many types of surface finishes on touch screen and surface displays. It is sometimes a user preference whether they prefer a glossy (mirror-like) or matte finish (dull but not mirror-like reflection). Determine if the DUT has a glossy or matte finish by observing an ambient light reflection.

2. Sparkle or Speckle Contrast

If the textured surface feature size is on the order of the DUT pixel size, sparkle will be present and is more apparent for specific colors. The sparkle looks like it is twinkling when ambient light is reflected off the surface. An example of sparkle is shown in Figure 17. If possible, compare the surface with and without the texture that causes the sparkle affect. The method described below is a visual determination. Methods have been proposed for measuring the sparkle of a display by comparing the distinctness of image of an uncoated and coated displays² and the speckle contrast compared to the glossiness of the display surface³.

ANALYSIS:

1. Determine whether the DUT has a glossy or matte finish. If the matte finish is very minimal the display will have both a specular and diffuse reflection.
2. Determine whether the DUT has sparkle or not by observing red, green, and blue images under typical ambient lighting and viewing angle conditions. Rate the amount of acceptable sparkle for each color (rank 1 to 10 with 1 being no sparkle and 10 being unacceptable sparkle).

REPORTING:

1. The final display test report should include the visual observations of the type of reflection observed in the typical ambient lighting conditions and at the typical viewing angle.
2. The final display test report should include the visual observations of the amount of sparkle observed in the typical ambient lighting conditions and at the typical viewing angle for each color. The ranking of sparkle is a subjective criteria and may differ from observer to observer and color to color. The ranking of the sparkle is a preliminary way to determine if the touch screen or surface display has unacceptable speckle which will impact the display quality.

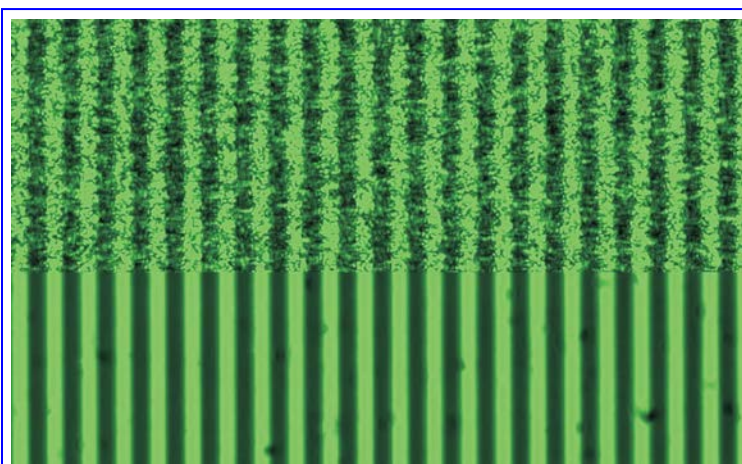


Figure 17. Line on/Line off pattern with and without speckle.

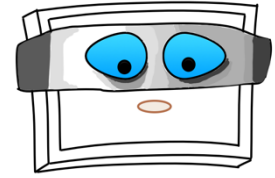
²SID 2011 Digest, Paper 70.4: Optical Characterization of Scattering Anti-Glare Layers by Michael E. Becker and Jürgen Neumeier.

³SID 09 Digest article: SID 09 DIGEST • 511 ISSN/009-0966X/09/3901-0511 36.2: Quantifying “Sparkle” of Anti-Glare Surfaces by Darren K. P. Huckaby and Darran R. Cairns (<http://www.sidmembers.org/proc/SID2009/36-2.pdf>).



19. NEAR EYE DISPLAYS VR/AR, HMDs

This chapter deals with the measurements of Near Eye Displays (NEDs) also referred to as Head Mount Displays (HMDs), with either occluded or see-through optics. Virtual Reality (VR) is mostly associated with the opaque optical configuration where the direct view of the outside world is completely blocked by the display and optics creating the display virtual image view. See through optic configurations are mostly associated with Augmented Reality (AR) as well as Head Up Displays (HUDs). The primary focus of this chapter is on virtual image producing displays worn on the face, which presents the largest technical challenge for metrology to obtain repeatable and reproducible results. However, most techniques and Light Measurement Device (LMD) requirements can be applied to HUDs as well. The chapter discusses methods and procedures for the characterization of display performance.



There exist a number of technologies used to create VR and AR Near Eye and Head Up displays shown in the following diagram. Figure 1 illustrates the complexity of the virtual image display family tree. The methods and LMD configuration requirements presented in this chapter should apply to all NEDs listed in Fig. 1. As new technologies are developed, the generic set of methods described will need to be evaluated to assure they still provide luminance, color, resolution, etc. measurement results that correlate to human perception.

The chapter covers the virtual display measurements that have corresponding measurements for flat panel displays. Since each virtual image display technology has its own unique set of challenges, we have placed all the common material in the introduction. This is a departure from much of the rest of this document where a separate metrology appendix and tutorial appendix are provided. (Note that some of the material in the appendices of the 3D and projection display chapters can also apply to virtual image displays and will be referenced when appropriate).

This chapter does not attempt to describe the 3D perception aspects of virtual image displays, since this topic is covered in Chapter 17. We focus on obtaining the monocular measurement results for the right and left eye positions that can be used to apply the methods of Chapter 17. Two binocular measurement results that are not covered in Chapter 17, virtual image distance versus convergence angle, and interpupillary distance, will be covered in this chapter.

Another important part of this chapter is establishing a precise terminology and descriptive geometric system for measuring virtual displays. To that end, we follow these introductory remarks by defining common terminology that are used in evaluating virtual image displays. Some of these concepts are rather complicated and difficult to understand; hence, the first section of this chapter is devoted to establishing the conceptual framework to further define some of these terms. Most of the methods in this document apply to direct-view as opposed to virtual-image displays described in this chapter. Fundamentally, the measurements and requirements are the same between the two types of displays. The major difference is the geometrical requirements of the LMD and how vantage point measurements are applied to virtual-image displays.

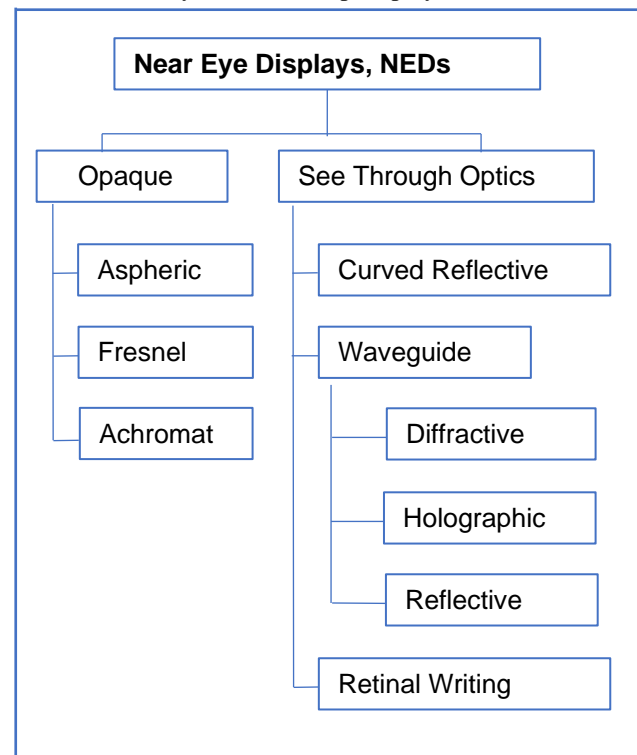


Fig. 1. List of NED types that have been measured using the methods in this chapter.

Terminology:

aperture stop – The aperture (opening) of an optical system that determines the amount of light by limiting what is transmitted. See Section 3.7

field stop – The aperture in the LMD that defines the sampled angular collection cone for measurement of luminance or color. (Refer to Fig)

entrance pupil - The image of the aperture stop as viewed in object space (from the front of the optical system). (Refer to SETUP Section 3.7 luminance meter nomenclature and Fig. 4)

exit pupil – The image of the aperture stop as viewed from the back of the optical system. See Fig. 2.

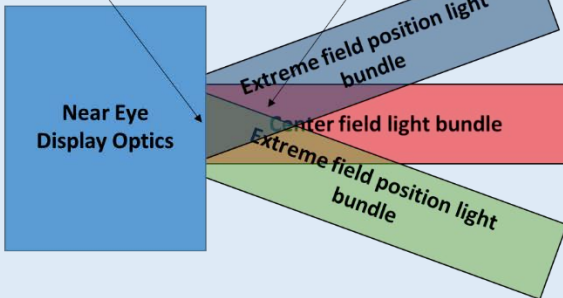


An internal pupil forming optical magnifier, or “simple magnifier” is a magnifier in which a) the image of the aperture stop is virtual or b) external to the magnifier and has no clearly defined aperture stop within the optical design or the aperture stop is outside the system or has no “real” image conjugate.

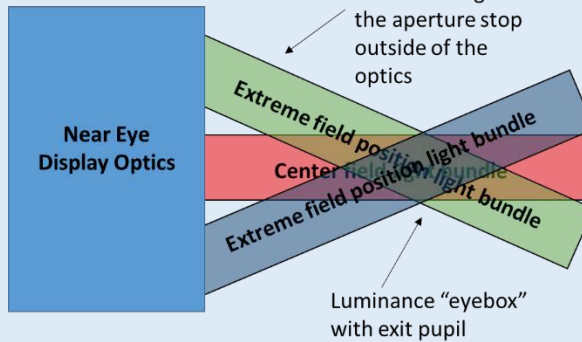
In an external pupil forming optical magnifier, a physical aperture stop exists within the optical design. The optical elements that are between the aperture stop and the user form a real image of the aperture stop at the defined plane. The “eyebox” of this system has its maximum two-dimensional area at the plane of the real image of the aperture stop, defined as the exit pupil.

Field position light bundles have no convergence outside the optics

Luminance “eyebox” with no exit pupil



Field position light bundles converge to a real image of the aperture stop outside of the optics



Luminance “eyebox” with exit pupil

Fig. 2. Internal pupil forming and external pupil forming NEDs. The exit pupil is an image of the aperture stop. The LMD entrance pupil is located at the exit pupil of the NED or within the eye box as show in Fig 3.

design eye-point (of a Device Under Test, DUT) – The center of the NED exit pupil, usually along the optical axis. For optimum viewing of the display virtual image, the eye pupil is generally designed to be placed at this position.

eye entrance pupil - The full diameter of the light gathering aperture of the eye, e.g., the diameter of the iris. 5 mm maximum diameter for NED measurements.

eye rotation point – Center of rotation for the human eye. A point on the optical axis of the eye between the cornea and the retina, 13 mm from the cornea and 10 mm from the eye entrance pupil. Center point for the north polar spherical measurement coordinate system for Eye Rotation Point measurements.

pupil rotation point – A point at the center of the entrance pupil and on the optical axis of the eye (or LMD). Center point for the north polar spherical measurement coordinate system for pupil rotation point measurements.

fovea –The area of the macula depression in the retina that has the highest concentration of cones and is the area of color discrimination and maximum visual acuity.*

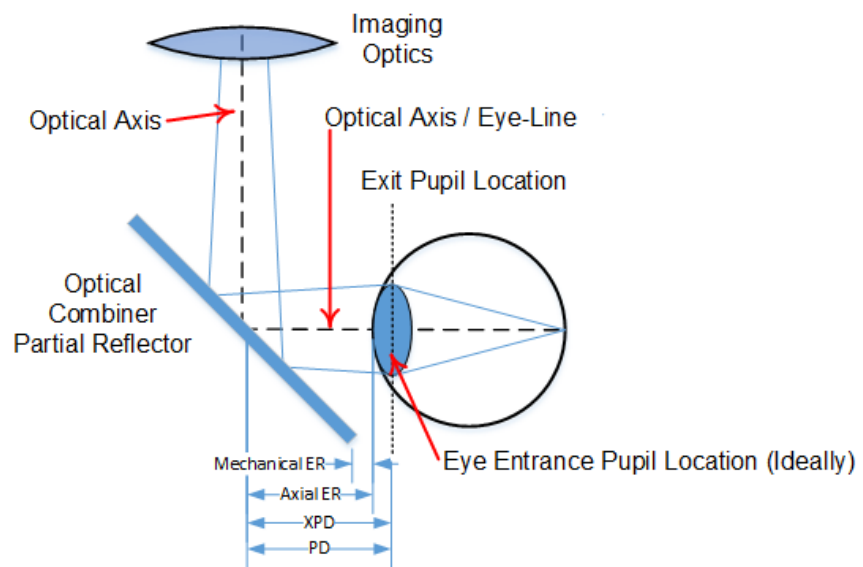


Fig. 3. Definition of terms; exit pupil distance (XPD) from last optical surface to system exit pupil (XP) location; pupillary distance (PD) from the last optical surface to the eye entrance pupil (EP) location; axial eye relief (ER) from the last optical surface to the vertex of the eye cornea; mechanical eye relief (ER) from the nearest part of the last optical element to the vertex of the cornea.



foveola -- The small depression in the center of the fovea, that contains only cones and Müller cells, and is the area of maximum visual acuity and color discrimination.*

eye relief – The distance between the last optical element of the DUT and the vertex of the cornea of the eye along the optical axis, also referred to as axial eye relief. See Fig. 3.

mechanical eye relief – The distance between the nearest part of the last optical or mechanical element of the DUT and the plane of the corneal vertex, also referred to as available eye relief.

exit pupil distance – The distance, along the optical axis, between the last optical element of the NED and exit pupil of the NED.

pupil distance – The distance, along the optical axis, between the last optical element of the DUT and the pupil plane of the eye. Also referred to as pupillary distance.

LMD field of view (FOV) – The full subtended field angle that can be observed by the LMD. (Refer to SETUP Section 3.7 luminance meter nomenclature, Angular field of view)

measurement field angle – Angle defined by the LMD field stop. (Refer to Fig. 4 and SETUP Section 3.7 luminance meter nomenclature)

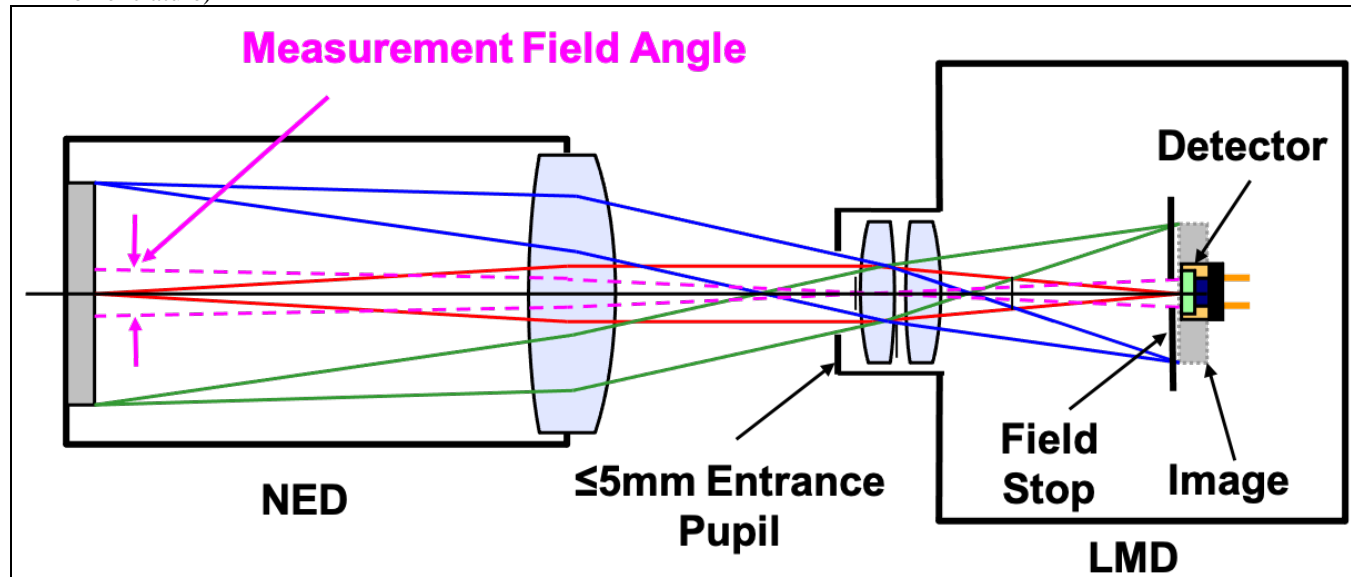


Fig. 4. Measurement field and measurement field angle are defined by the LMD field stop and the LMD field stop image on the display. If the display is virtually at infinity, the measurement field can only be defined as the measurement field angle.

virtual image field of view (FOV) – The full subtended field angle of the DUT virtual image (usually based on luminance) as observed nominally from the eye-point.

DUT field of view (FOV) – The full subtended field angle of the DUT as observed nominally from the eye-point., containing the virtual image and any surrounding area (in the case of augmented reality). Abbreviated: DUT FOV.

eyebow – The volume, defined in a right-handed x-y-z Cartesian coordinate system, around the eye-point where the entire virtual image FOV can be observed without degradation. The measurement results are dependent on the pupil size of the LMD and the measurement parameter (e.g., luminance, color or Michelson contrast) used to determine the field of view boundary. Eyebow is also referred to as Qualified Viewing Space (QVS) in ISO 9241-305 6.11.11 P 23.13 †

boresight alignment - process to bring into parallel alignment the optical axis of an electro-optical (EO) imaging/projecting/laser system with a certain reference optical axis or reference mechanical axis. This is typically accomplished using an autocollimator.

array LMD- A term used interchangeably with “imaging LMD” and “2D LMD”. Imaging LMD is the preferred term used in other international standards. An LMD using any of a variety one and two-dimensional light detectors: Linear diode array, linear CCD array, CCD detector or CCD camera (two-dimensional array), CMOS arrays, and others. Often such devices have a substantial sensitivity to infrared light so that a photopic filter is needed to make accurate measurements of luminance.

* Tschulakow AV, Oltrup T, Bende T, Schmelzle S, Schraemeyer U. 2018. The anatomy of the foveola reinvestigated. *PeerJ*6:e4482 <https://doi.org/10.7717/peerj.4482>

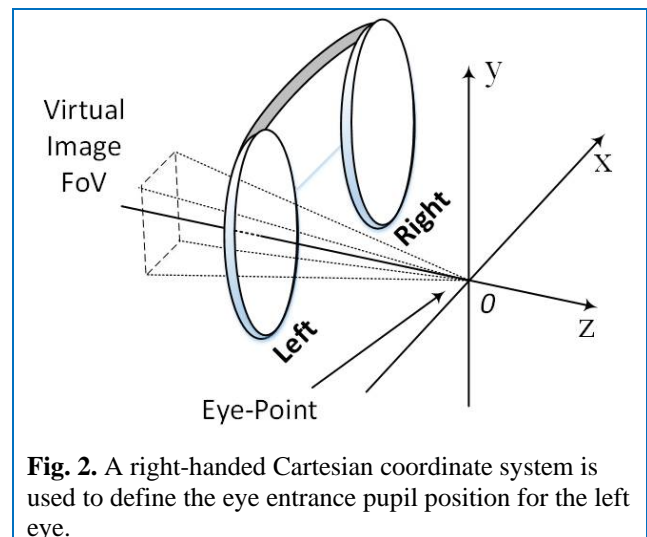
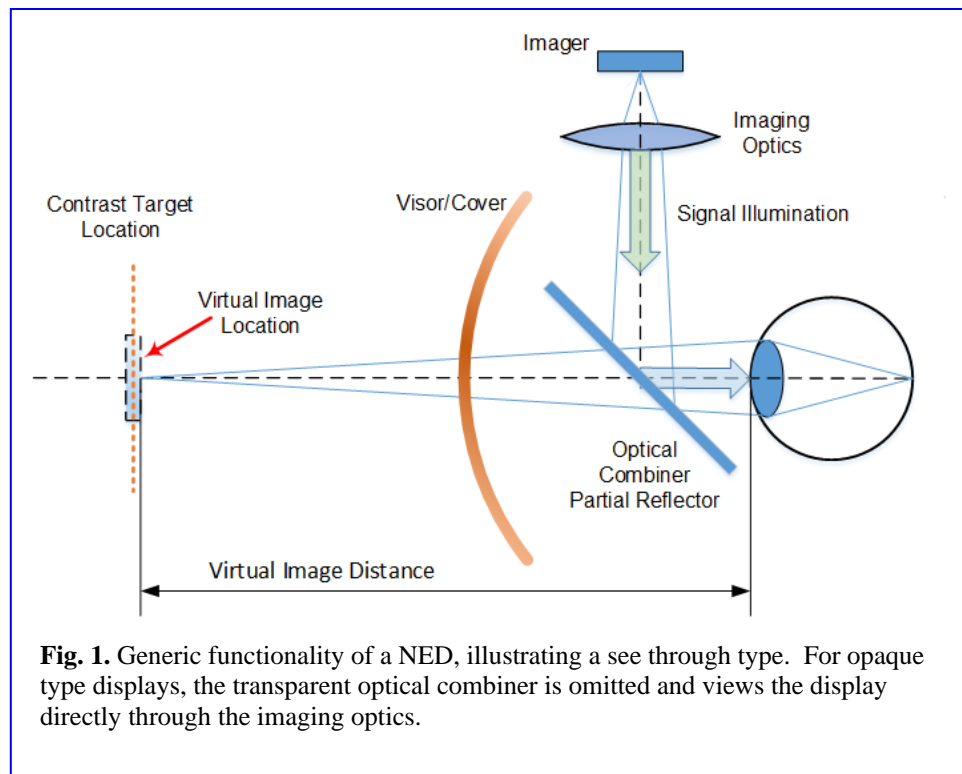
† ISO 9241-305:2008(E)



19.1 GEOMETRY OF VIRTUAL DISPLAY AND MEASUREMENTS

The geometric setup of NEDs and HUDs differ from fixed flat panel displays because a virtual image is produced by an optical system. Figure 1 illustrates the generic functionality of a near-eye display. A real image is initially generated by an imager or projector. This image is then relayed by the NED optics and combiner to the eye. For AR displays, the semi-transparent combiner allows the projected image to be overlaid on the real scene viewed through the NED. For VR displays, the combiner would be an opaque (ambient world blocked) reflecting surface or not included in the optical design, and only the virtual image created by the imager can be viewed. However, in both AR and VR devices, the rays off the combiner are diverging and require the lens of the human eye to project a real image on the back of the retina. Therefore, the LMD and its setup must accurately emulate the optics and placement of the human eye. The purpose of this section is to highlight the differences between virtual displays and flat panel displays to better guide the user in the proper setup for NED measurements.

The geometry of the measurement setup is described by a standard coordinate system. The rectilinear motion and position of the entrance pupil is described in terms of the Cartesian coordinate system. The basic definition described in section 3.6 for the Cartesian coordinates apply in this chapter, but with some important changes. The origin of the right-handed x-y-z Cartesian coordinates is the design eye-point for one of the eyepieces of the display (see Fig. 2). The z-axis is perpendicular (normal) to the virtual image and often serves as the optical axis of that eyepiece. The x-axis is horizontal from the design eye-point and the y-axis is vertical. A second coordinate system, to be discussed shortly, is also needed to describe the viewing direction of the eye or LMD.





A simplified model of a standard eye geometry is shown in Fig. 3 with two geometric reference points marked by an “x” and a red dot. The x is centered in the plane of the eye entrance pupil. It defines the pupil rotation point. The red dot is the center of eye rotation and defines eye rotation point. The distance from the cornea vertex to the center of the pupil (pupil point) is 3 mm. The distance from the pupil point to the eye center of rotation is 10 mm.

Two different positions are referenced as the center of the spherical coordinate system used to define viewing direction. One is the pupil rotation point and other is the eye rotation point. For the pupil rotation point, the pointing direction coordinate system is centered at the origin of the NED cartesian coordinates (see left side of Fig. 4). For the eye rotation point, the pointing direction coordinate system is located on the z axis 10 mm from the origin of the Cartesian coordinate system (see right side of Fig. 4).

In the case of pupil rotation (left image in Fig. 4), there is a shift of the center rotation point of the eye when pivoting about the pupil rotation point as it maintains its position at the NED design eye-point. This is an unrealistic eye movement, as it would require the eye to pop out of its socket. The right-hand image in Fig. 5 illustrates the natural rotation of the eye about the eye rotation point, 10 mm behind the NED design eye-point along the z-axis. In the eye rotation case, the center of the eye pupil moves farther away from the design eye-point with increasing elevation or azimuth angles.

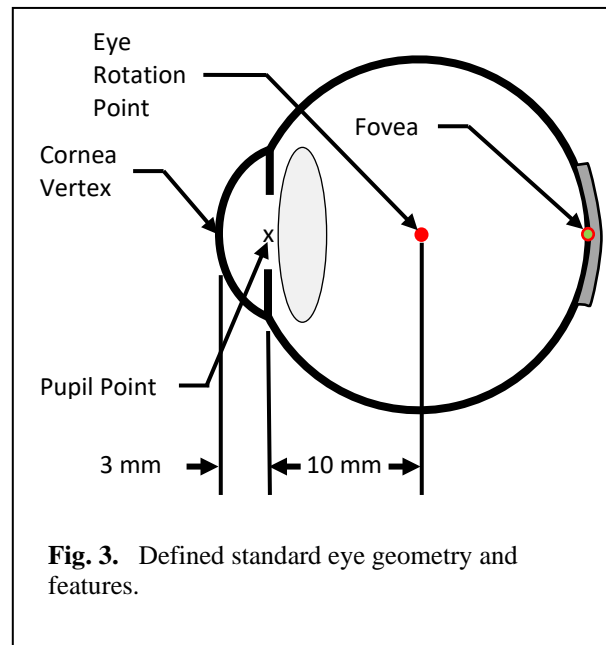


Fig. 3. Defined standard eye geometry and features.

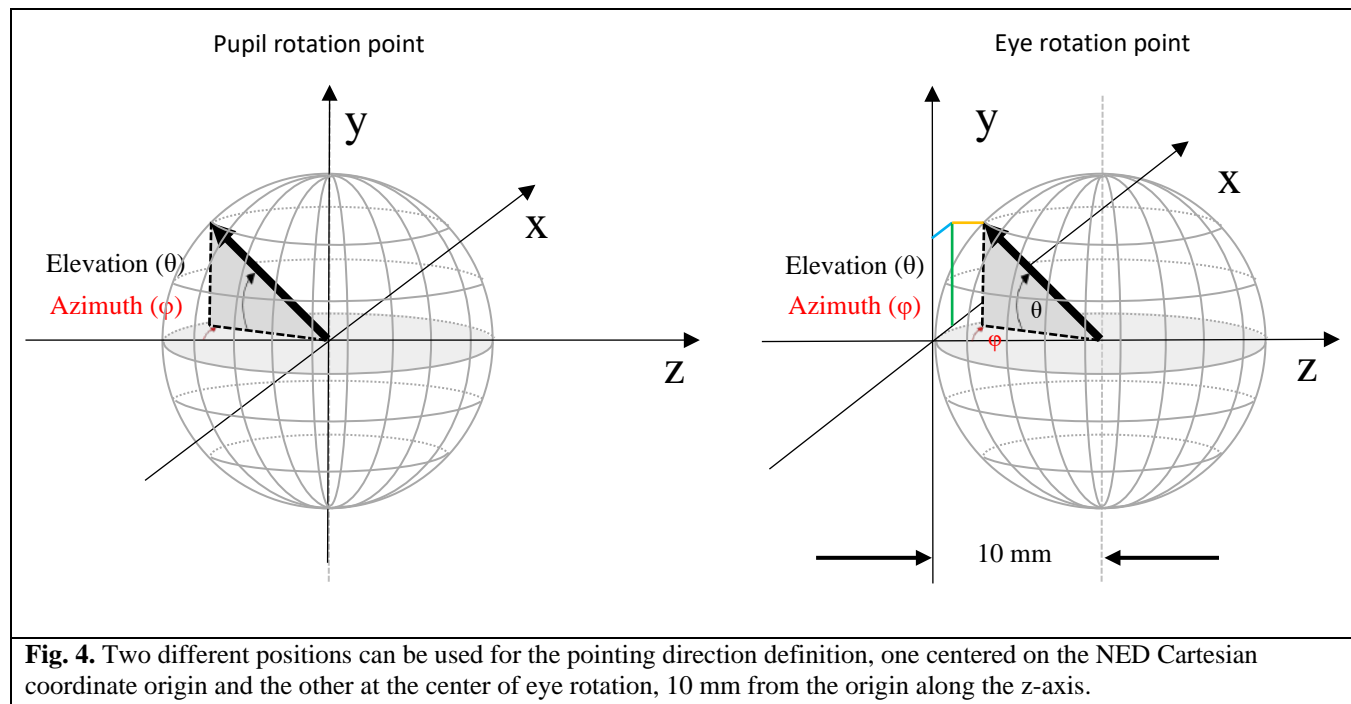


Fig. 4. Two different positions can be used for the pointing direction definition, one centered on the NED Cartesian coordinate origin and the other at the center of eye rotation, 10 mm from the origin along the z-axis.

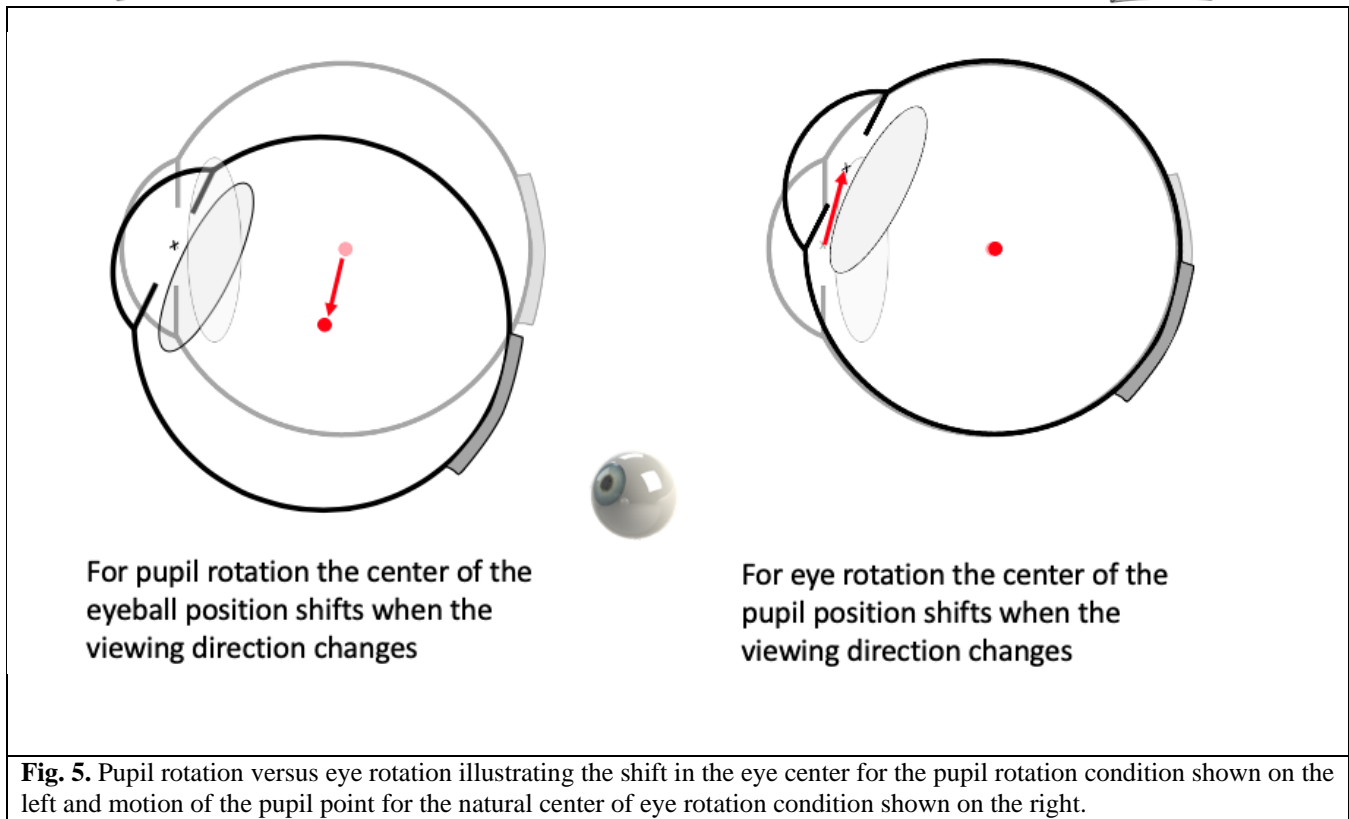


Figure 6 shows the eye rotation motion of the eye entrance pupil from the right side of Fig. 4 in more detail. Equation 1 describes the center position of the entrance pupil as it moves away from the NED Cartesian coordinate origin (design eye-point) in the case of eye rotation. Figure 7 plots the displacement of the entrance pupil from the origin with increasing eye rotation. The rotation method (pupil or eye rotation) must always be reported with the pointing direction (in spherical coordinates) for NED measurements since the results can be very different between the rotation methods. The pupil rotation position captures the light only from a fixed pupil position (usually the design eye-point of the NED device) and does not include the influence of eye rotation (gaze). Pivoting about the eye rotation point is the preferred pointing direction method since it moves the LMD entrance pupil over the design eye box in the same manner that a user's eye pupil as it collects the ray bundle from the NED.

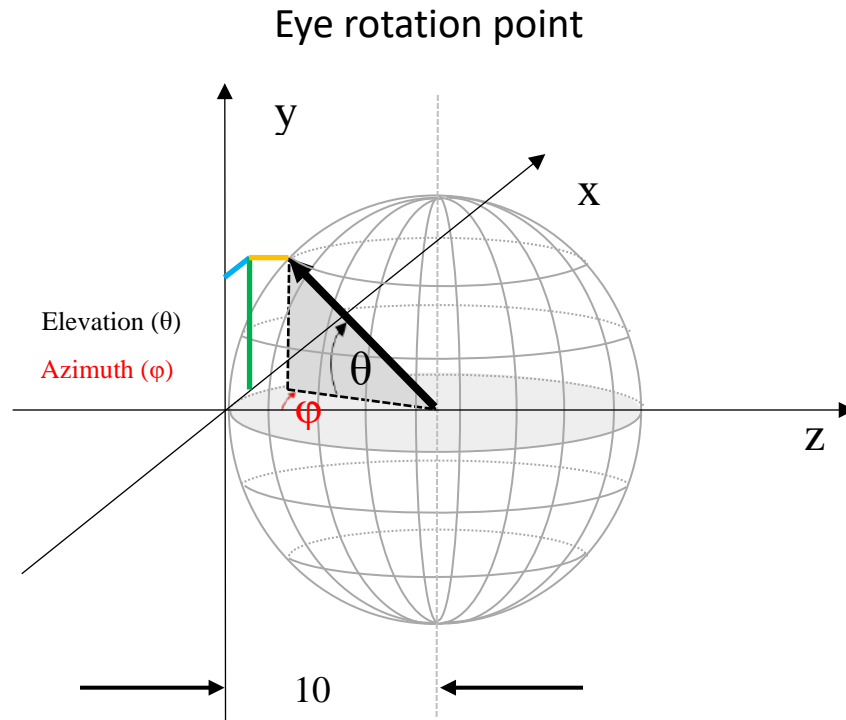


Fig. 6 Detail of the eye rotation locations of the eye pupil that result from a change in gaze angle with the center of rotation 10 mm from the origin to emulate the human eye rotation point and movement through the NED eye box

$$\begin{aligned} X_p &= 10 \cos \theta \sin \varphi \\ Y_p &= 10 \sin \theta \\ Z_p &= 10(1 - \cos \varphi \cos \theta) \end{aligned}$$

Equation 1 The X_p , Y_p , Z_p coordinate locations of the eye pupil that result from a change in gaze angle with the center of rotation 10 mm from the origin to emulate the human eye rotation point and movement through the NED eye box

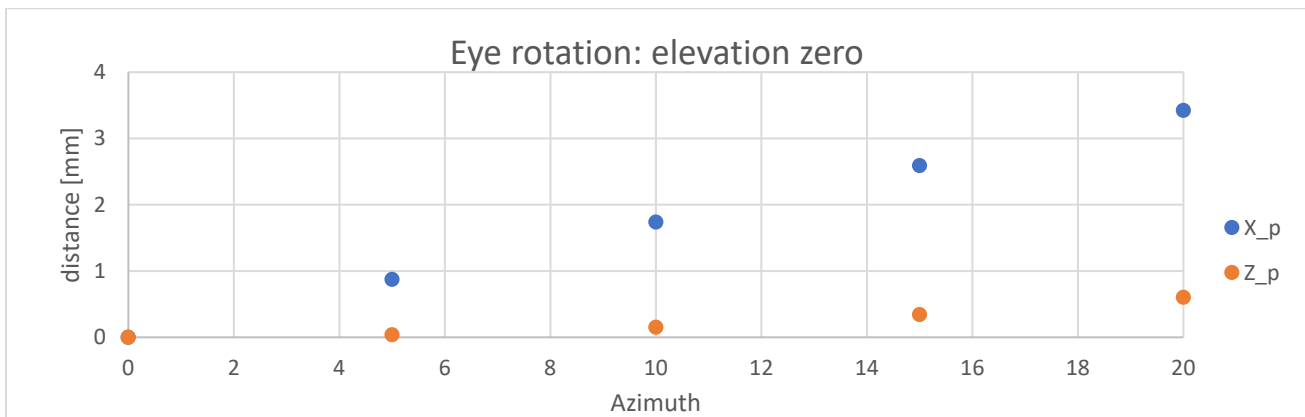


Fig. 7 This graph illustrates the amount of pupil walk in 5 degree increments as described by Equation 1.



19.2 LMD requirements for NED measurements

Light Measurement Device (LMD) or Detector for NEDs: Appendix A1.3.10 Appearance to the Eye vs. the LMD, describes the differences between the eye entrance pupil, typically 2 mm up to 5 mm diameter and most LMDs having larger diameters, 25 mm and larger. This section was an early predictor of the exact requirements needed for NED measurements. For most display applications, the space over which the display can be viewed is relatively large. Therefore, LMDs have

often taken advantage of that and designed optical systems with 25 mm diameter and larger aperture stops and entrance pupils to collect more light. Now, studies have shown that LMDs used for direct view displays with large entrance pupils are not appropriate for NED measurements, and report large errors in luminance and color.^{1,2} Beyond this entrance pupil size difference, LMDs for NED measurements must have relatively high precision mechanical positioning and pointing direction capability. This is required to better simulate the human eye entrance pupil size and positioning and make repeatable and reproducible measurements on NEDs. The precise positioning requires at least 5-axis motion for x, y, z axis for translation, and both azimuth ϕ and elevation θ pointing directions.

The measurements we want to make include:

Luminance, both photometric (with a filter and detector) and spectroradiometric,

Color, both colorimetric (with a filters and detector) and spectroradiometric,

Gray scale,

Spatial measurements including contrast ratio, Michelson contrast and resolution.

The following additional measurement items rely on specific LMD optical properties, as well as adjustable mechanical pointing direction and translation positioning stages, include:

Luminance uniformity,

Color uniformity,

Eye box volume,

Virtual image geometric distortion,

Field of view.

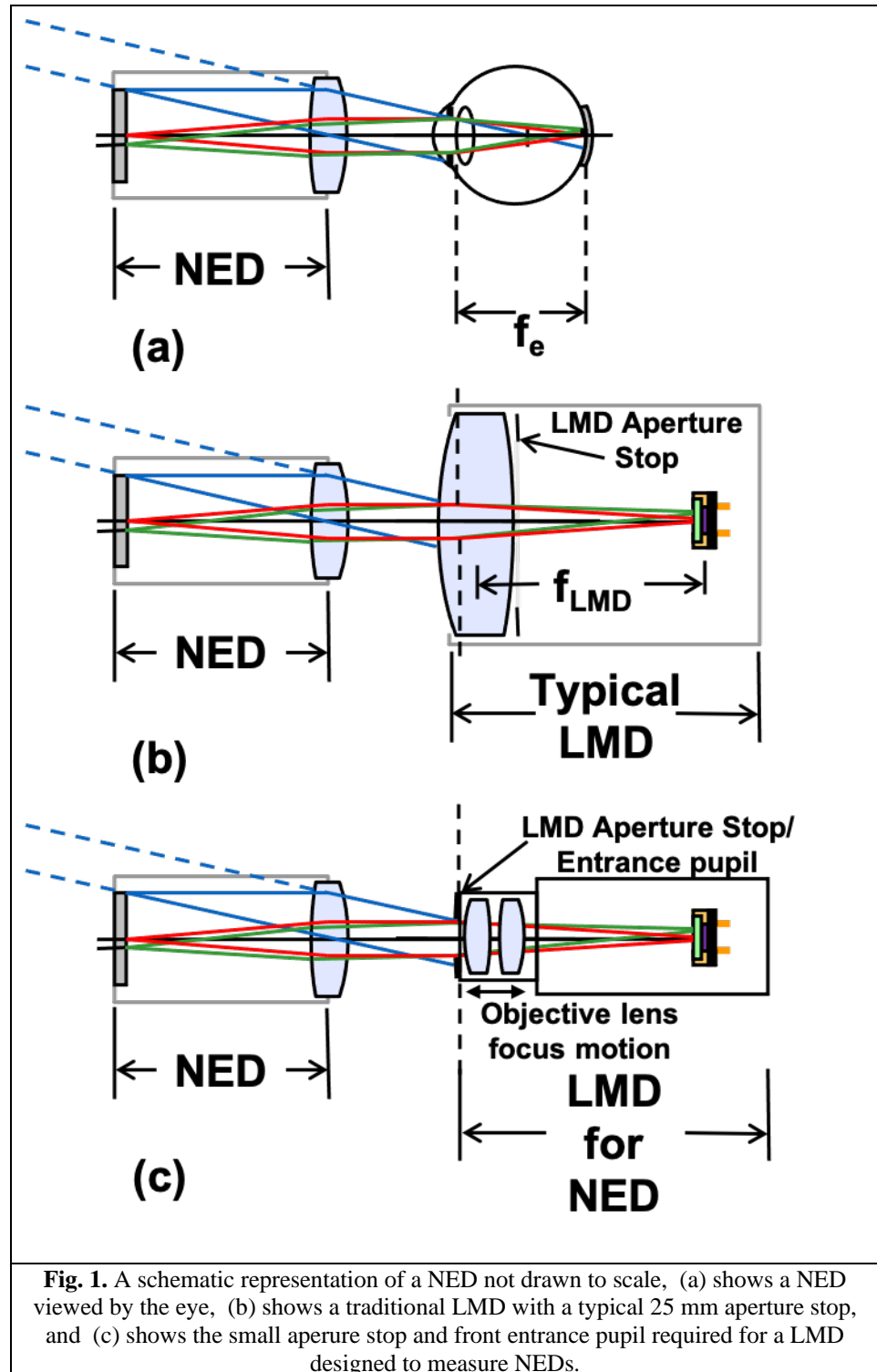


Fig. 1. A schematic representation of a NED not drawn to scale, (a) shows a NED viewed by the eye, (b) shows a traditional LMD with a typical 25 mm aperture stop, and (c) shows the small aperture stop and front entrance pupil required for a LMD designed to measure NEDs.



Figure 1 illustrates the challenge of measuring a NED and getting results to correlate with what the eye sees through a 2 mm to 5 mm diameter iris opening (see A1.3.10). In 1(a) the eye is represented collecting a 2 degree spot within the center of the virtual image. In 1(b), the eye is replaced by a LMD on the optical axis with a typical 25 mm diameter aperture stop. The aperture stop is typically somewhere within the optical system. When the LMD is calibrated, luminance or spectral radiance measurements are only valid when the entrance pupil, which is the virtual image of the aperture stop (refer to section 3.7), is completely filled with light from the spatially uniform standard source. However, NED designs assume that the viewer has a small pupil diameter (typically ≤ 5 mm diameter), so the light fields created by these NEDs are typically not that much larger than this pupil size. Matching the size range of the eye entrance pupil is the primary reason that the LMD must have no more than a 5 mm diameter entrance pupil, and must be placed in the same plane as the eye's entrance pupil to make radiance, luminance or color measurements.^{2,3} This 2 to 5 mm range of LMD entrance pupil sizes is also appropriate for evaluation of NEDs implementing Maxwellian view, retinal writing technology, which can be explained with Fig. 2.⁴ For NEDs producing light fields as illustrated by the example in Fig. 2 (a), the human eye entrance pupil is completely filled by the rays from the NED. Therefore, this condition also needs to be fulfilled for the LMD as shown in (b). Thus, the aperture of the LMD entrance pupil needs to be smaller than the eyebox to fulfill this "overflow condition". If the LMD aperture is larger, then the measured luminance values will not be correct. In the case of Maxwellian view retinal writing technology all rays are focused into the eye as shown in Fig. 2 (c). The eye entrance pupil is underfilled. In this particular case the condition is that all rays need to be captured by the LMD to get the

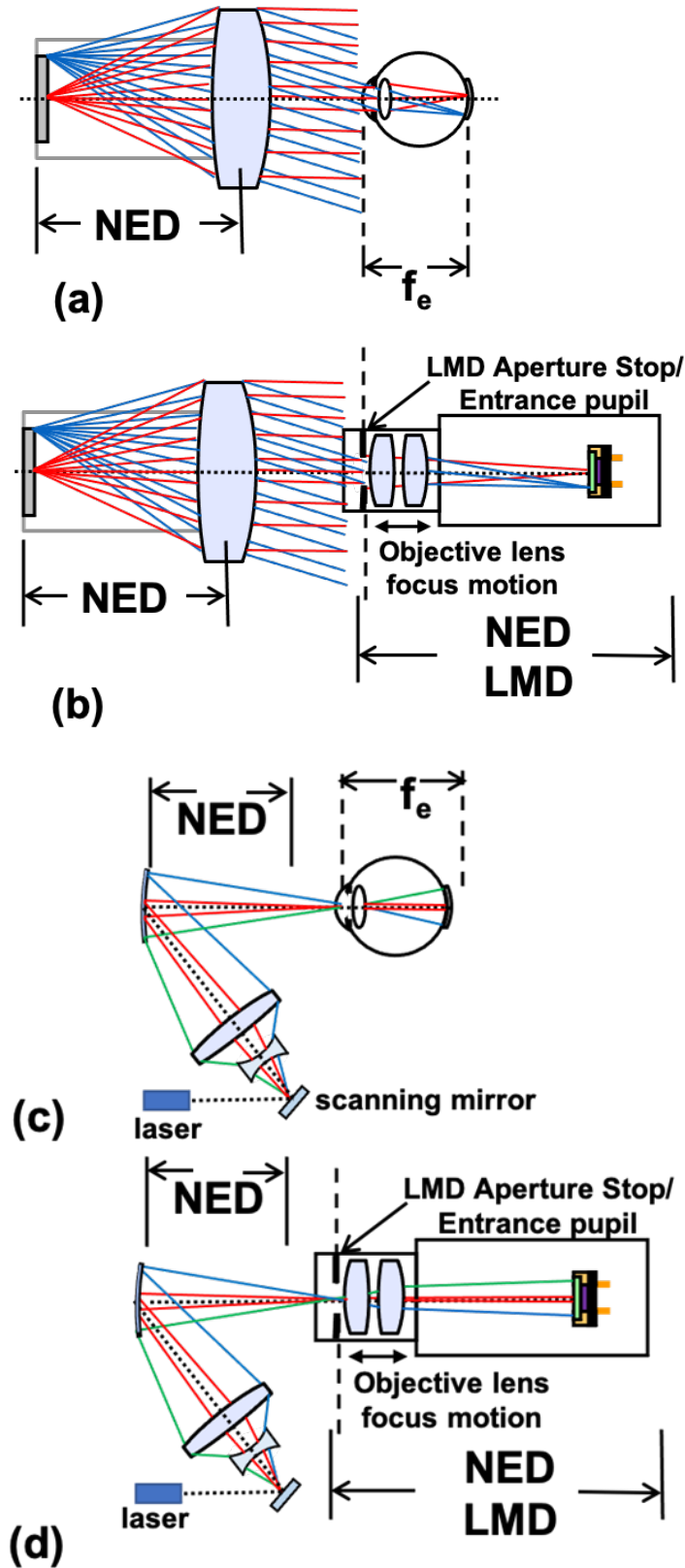


Fig. 2. In (a) the LMD entrance pupil filling condition for different types of NEDs: Eye in light field, (b) LMD in light field, (c) Eye in Maxwellian view and (d) LMD in Maxwellian view retinal writing technology



correct luminance values as shown in Fig. 2 (d). The “overflow condition” does not need to be met, however it is necessary to have uniform sensitivity over the full entrance pupil. ⁴

It is important to note that the size of the entrance pupil alone does not guarantee a correlated measurement between the LMD and “what the eye sees” because the field of view, stray light behavior and resolution of the LMD depend on the overall LMD and lens parameters (e.g., focal length, MTF, spherical aberration, coma, etc.). The entrance pupil size ensures correct photometric measurements with respects to the LMDs calibration. In order to precisely mimic eye rotation measurements, the entrance pupil of the LMD should mimic that of the human eye pupil, which is between 2 mm and 5 mm diameter. Otherwise, the captured luminance projection will not correlate to “what the eye sees”.

It is possible to design a LMD for a NED (just called LMD for the rest of this section and chapter) with an aperture stop behind the front optics only if three conditions are met, 1) the entrance pupil location is marked on the LMD so it can be positioned relative to the NED design eyepoint, 2) the virtual image of the aperture stop, the entrance pupil, should be between 2 mm and 5 mm and 3) the entrance pupil diameter must be known so it can be included in the test reports for the NED device under test (DUT). Another essential performance aspect regarding the LMD entrance pupil is that its position, relative to the NED being measured, should remain constant. If the entrance pupil is not kept at a constant position or, if moved, account for measurement difference as a function of position during LMD focusing. This is because large

performance changes can occur with small displacements of the LMD entrance pupil from the NED eyepoint or at any point within the eyebox. Some NED manufacturers may want to use entrance pupils smaller than the 2 mm that correlates to eye performance. For example, if a 1 mm diameter entrance pupil is used to measure the eyebox, the measurement will report results that may be larger but most certainly different than would be measured with a 2 or 5 mm entrance pupil. Also, a 2 mm entrance pupil may yield larger eyebox measurements than 5 mm. If all parties involved agree, using a smaller entrance pupil is acceptable and must be reported with the measurement results.

Also shown in Fig. 3 is the field stop aperture. The purpose of this aperture is to limit the light collection on the detector to a specific angular cone measurement field angle (such as 2 degrees). As with measurements of luminance and color for direct view displays described in section 3.7 and Appendix A1.2, this 2-degree full angle limit is typically the maximum standard field angle size.

In Fig. 2, light passing through the 2-degree field stop aperture typically goes through a photometric filter and then onto the sensor surface, in this case a representation of a silicon photodiode. This configuration can correctly measure luminance.

There are several LMD configurations that can be implemented which can suitably measure NED performance characteristics (e.g., luminance, color, and Michelson contrast) while maintaining the basic LMD requirements of ≤ 5 mm entrance pupil aperture and ≤ 2 -degree full angle field. Figure 4 shows a configuration where the spot-type LMD field stop, photometric filter and silicon photodiode are replaced by a 2D image sensor. The 2D image sensor consists of an array of small individual sensors that can provide photometric measurement. The appropriate number of pixels on the 2D sensor that

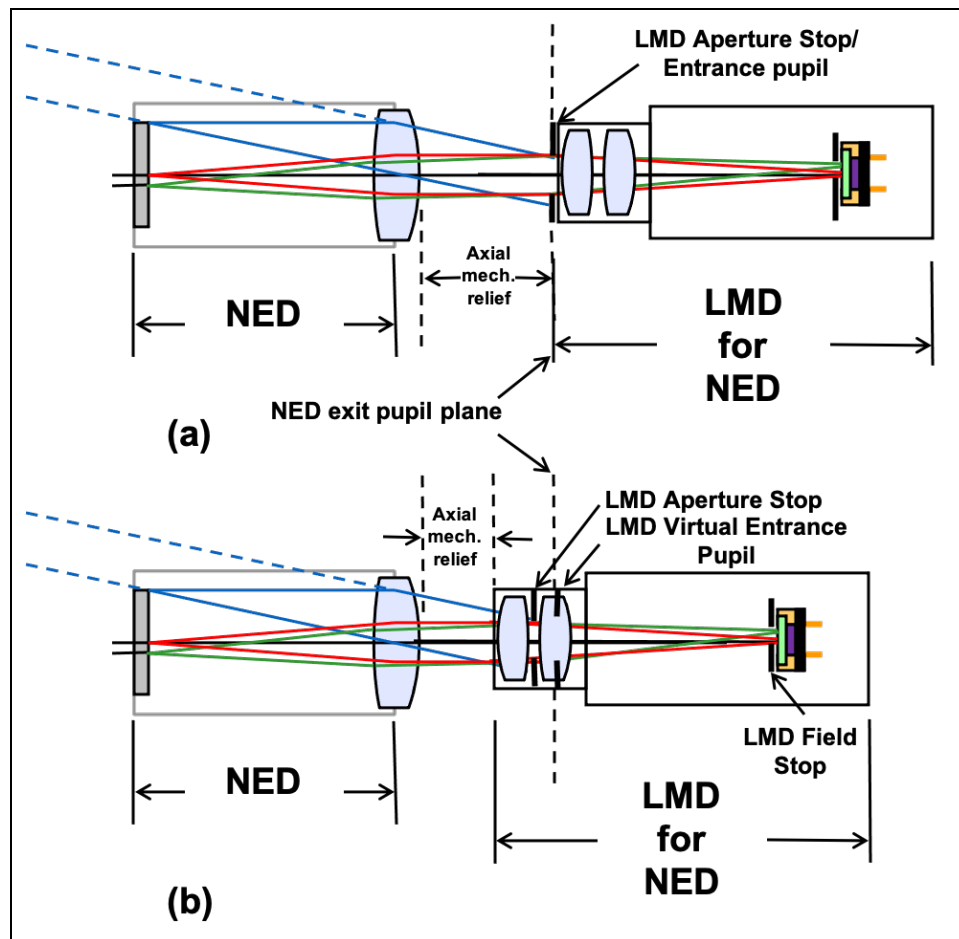
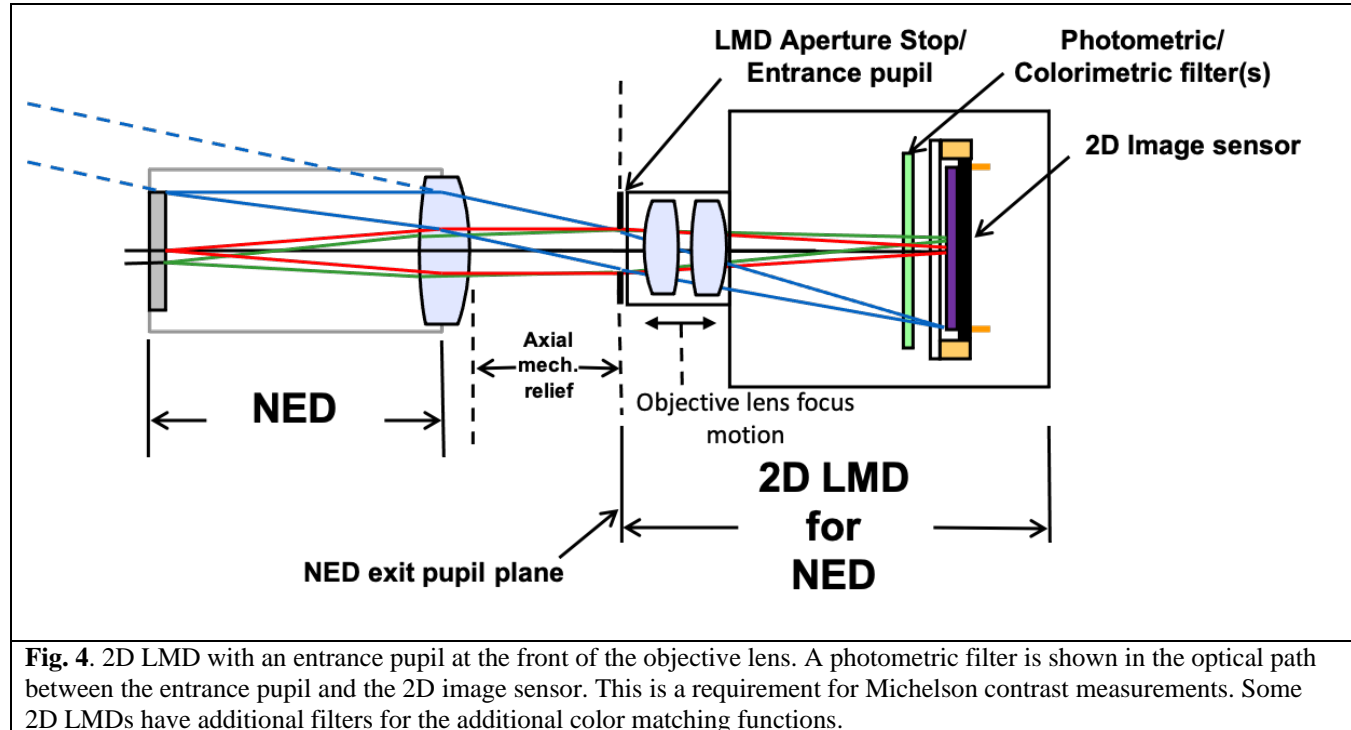


Fig. 3. In (a) the LMD entrance pupil is at the front of the LMD. This configuration allows the largest axial mechanical relief between the NED and the LMD as well as distortion free presentation of the entrance pupil. In (b) the aperture stop virtual image plane is the entrance pupil plane that must be positioned coincident with the NED exit pupil plane, reducing the axial eye relief.



corresponds to a 2-degree field stop area can be averaged to measure luminance, based on the number of 2D image sensor pixels per degree of measurement angle. A spot-type LMD, as well as 2D LMDs, can have additional filters that provide colorimetric in addition to photometric measurement capability.



Also, with this configuration, the focusing motion of the objective lens must be independent of the LMD entrance pupil position. It is worth noting that focusing motion of the objective lens is not the only method possible to focus the NED virtual image on the 2D sensor. Other options include moving the image sensor along the LMD optical axis or changing out the lens to cover a different depth of focus range defined by the entrance pupil size and lens focal length.

The minimum required configuration of the 2D LMD is shown with a $V(\lambda) = \bar{y}(\lambda)$ photometric (photopic) filter. Some 2D LMDs also have the additional filters for the \bar{X} and \bar{Z} color matching functions that can be mechanically interchanged. Some spectral mismatch exists in all tristimulus filters matched to detectors which leads to errors in color measurements. The measurement results can be significantly improved by using spectral measurement data and applying the CIE spectral mismatch correction factor. The spectral mismatch correction factor is calculated for the photometric value as shown in equation Eq. (1).³ Use of the equation requires spectral measurements of the unknown source in this case and NED, the spectral sensitivity of the detector and filter combination. The same spectral mismatch correction shown in equation 1 for the $V(\lambda) = \bar{y}(\lambda)$ photometric (photopic) filter can be applied to the other two the \bar{X} and \bar{Z} color matching functions.

NOTE 1 Most photometers are designed to simulate the $V(\lambda)$ function and calibrated using a source corresponding to CIE Standard Illuminant A. For such a photometer, the correction factor may be calculated using the equation:

$$F^* = \frac{\int_{\lambda} S(\lambda) V(\lambda) d\lambda \int_{\lambda} S_A(\lambda) s_{rel}(\lambda) d\lambda}{\int_{\lambda} S(\lambda) s_{rel}(\lambda) d\lambda \int_{\lambda} S_A(\lambda) V(\lambda) d\lambda} \quad (1)$$

where $s_{rel}(\lambda)$ is the relative spectral responsivity of the photometer, and $S(\lambda)$ and $S_A(\lambda)$ are the respective relative spectral power distributions of the light source to be measured and CIE Standard Illuminant A.

NOTE 2 This correction factor was formerly known as "colour correction factor".

NOTE 3 This term can also be applied to other radiometers whose response is intended to simulate a particular observer function, such as actinic radiometers.

Figure 5 shows a variation of the spot-type LMD in Fig. 3(a) by replacing the photometric filter and photodetector with an optical system that couples light into a spectroradiometer.

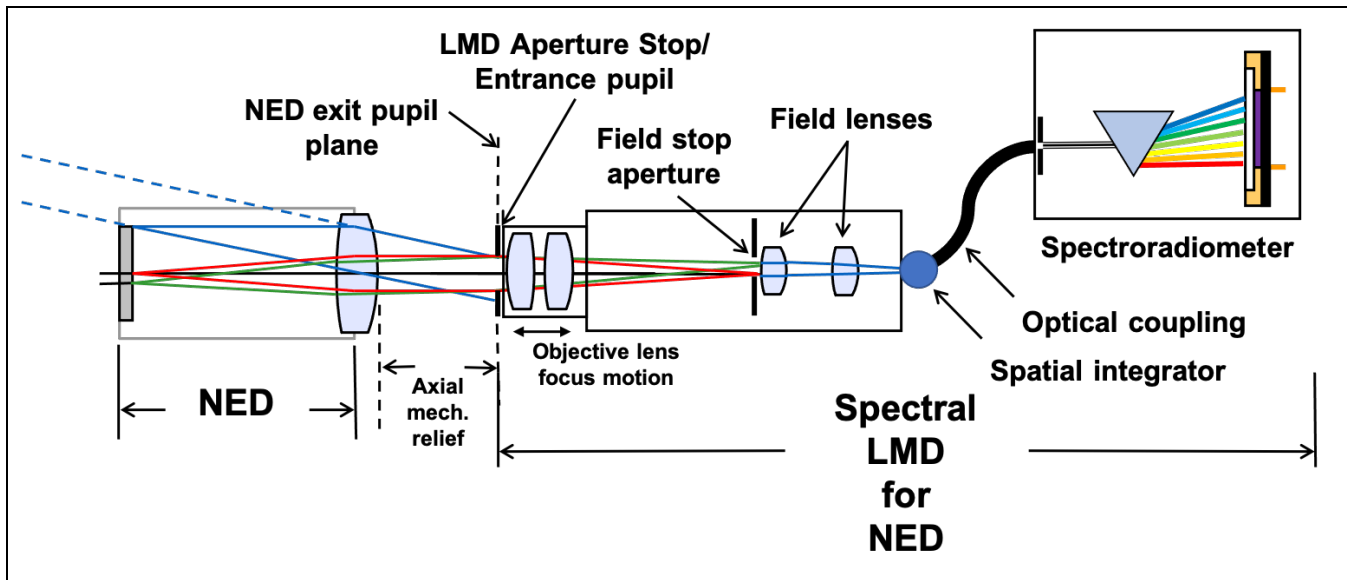


Fig. 5. Spectroradiometric LMD with the entrance pupil at the front of the LMD allows the largest axial mechanical relief between the NED and the LMD as well as distortion free presentation of the entrance pupil. The field lens system in this configuration is designed to maintain the radiometric calibration with a constant solid angle collection cone size over the range of objective lens focus settings.

The lenses shown after the field stop are referred to as a field lens system, or simply field lens if only one lens is used. Field lenses serve two purposes, 1) they increase the field of view of a detector (Smith, 1990)⁶ and 2) allow for the focus adjustment on the virtual image without effecting the radiometric collection efficiency. (Budde, 1983)⁷ The coupling to the spectroradiometer may or may not include a spatial homogenizer or integrator. The purpose of the spatial homogenizer (for example an integrating sphere or diffuser) is to provide uniform sensitivity of the spectral measurements over the entire entrance pupil. This uniformity is most important for repeatable and reproducible measurements of NEDs that have a highly non-uniform light distribution in the eyebox. An example is a NED that use retinal writing technology to produce the Maxwellian view virtual image, which has less than a 1 mm diameter at their exit pupil. In this case a 2-5 mm diameter LMD entrance pupil aperture will give measurement results that correlate with the users experience of the eyebox size and field of view. The LMD entrance pupil should be chosen to correspond to the 2-5 mm diameter adaptation range depending on the total (ambient plus NED) illumination level at the eye pupil for the NED being measured. There are various types of optical coupling possible between the output of the field lens system and the entrance slit of the spectroradiometer. Some LMDs use a fiberoptic light guide to couple the light collected through the field stop aperture, while other LMDs may have a direct coupling to the image of the entrance pupil into the spectroradiometer entrance aperture. Proper calibration and use of array detector spectroradiometers is detailed in CIE publication 233.⁸

Another method of collecting the light into the spectroradiometer is shown in Fig. 6. In this configuration a fiberoptic light guide couples all the light passing through the field stop aperture and transfers it to the entrance slit of the spectroradiometer. The portion of the light passing through the entrance slit is then measured to determine the intensity as a function of wavelength. In this configuration, where field lenses are not used, addition of a radiometric stop aperture is required to maintain a constant solid cone collection angle into the end of the fiberoptic light guide.

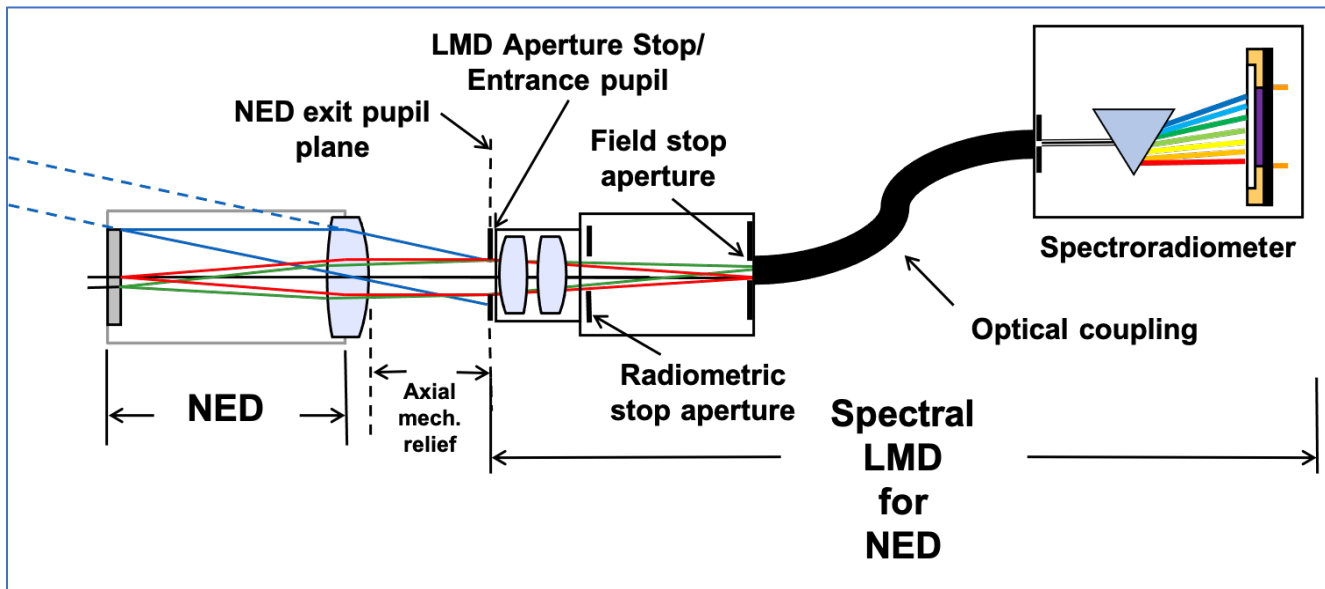


Fig. 6. The LMD configuration shown here collects light that passes through the field stop directly into a fiberoptic light guide and delivers a portion through the entrance slit of the spectroradiometer. In order to maintain an amplitude calibration over a range of focus positions without field lenses, a radiometric stop aperture must be used. (Budde, 1983)⁷

The final LMD configuration considered here is a combination of the 2D LMD and the spectroradiometer LMD shown schematically in Fig. 7. Starting from the basic 2D LMD configuration shown in Fig. 4, a mirror surface is inserted into the optical path between the entrance pupil and the 2D sensor. Light reflecting off the mirror surface is directed to a field stop aperture which selects the 2 degree measurement field angle for spectral based luminance and color measurement. Various methods are used to place the mirror in the optical path: 1) permanently mounted beam splitter which covers the complete light ray bundle traveling through the entrance pupil, 2) beam splitter inserted mechanically when spectral measurements are required for color or luminance, 3) mirror inserted mechanically when spectral measurements are required for color or luminance as well as other methods.^{8,9} Whichever method is used to sample the light, polarization independence must be maintained.⁸ In addition to the entrance pupil size and detector configurations of LMDs are the positioning and pointing direction considerations required for measurements of NEDs. The control of the LMD entrance pupil position relative to the NED is extremely important for repeatable and reproducible measurement results.

Spatial characteristics such as Michelson contrast, not only color and luminance, need to be measured by the LMD. For things like uniformity a spot LMD can be used but a 2D LMD is required for higher spatial measurements. More details of the configuration of a 2D LMD are shown in Fig. 8.

In addition to the entrance pupil size and detector configurations of LMDs are the positioning and pointing direction considerations required for measurements of NEDs. The control of the LMD entrance pupil position relative to the NED is extremely important for repeatable and reproducible measurement results.

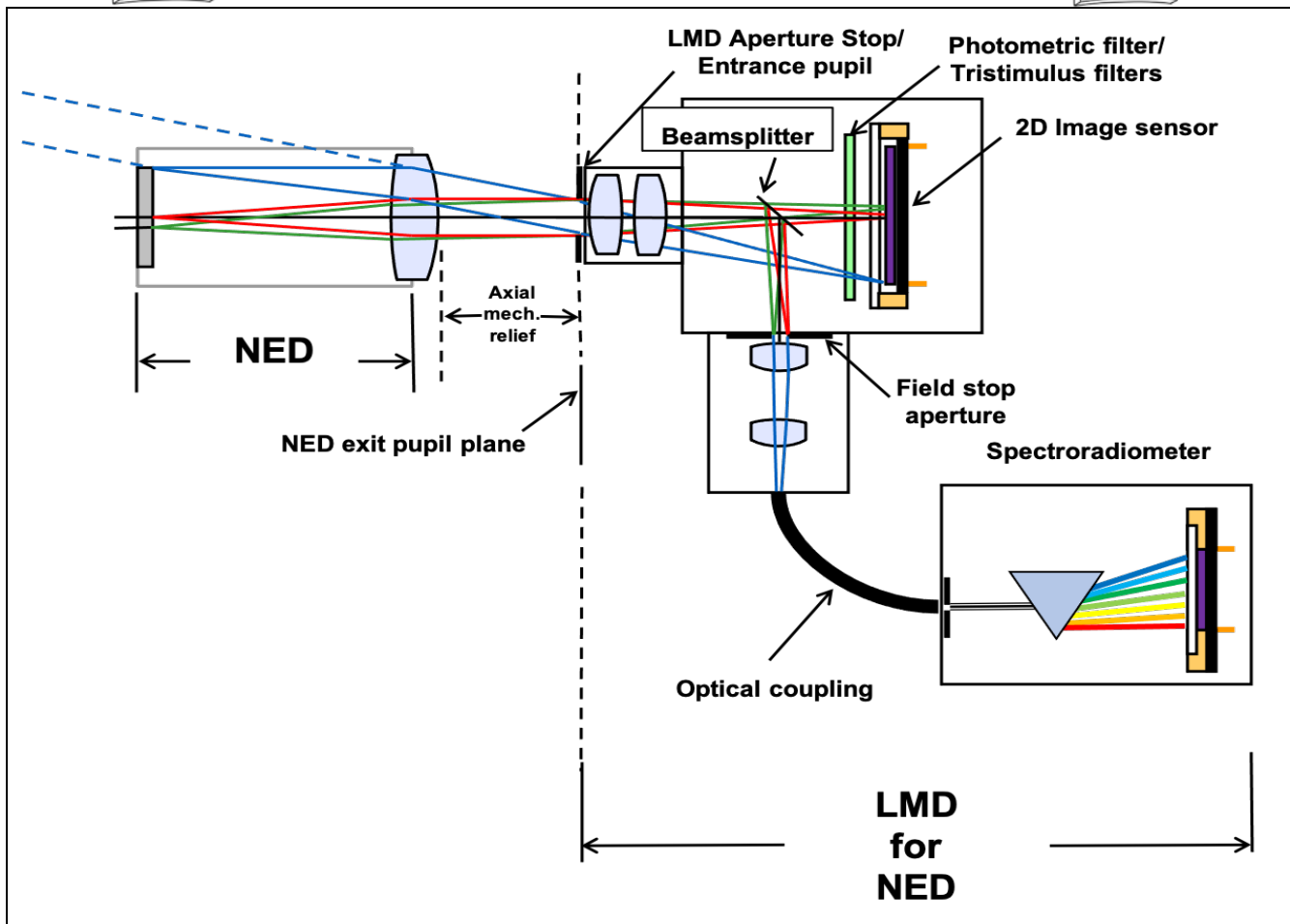


Fig. 7. A LMD configuration combining a 2D LMD and a spectral LMD is shown here. The advantage is the ability to apply the spectral mismatch correction factor to the luminance and color measurement made with the 2D camera based on the spectral measurements of the NED and the spectral response of the particular color matching function of the filter/camera sensor combination.

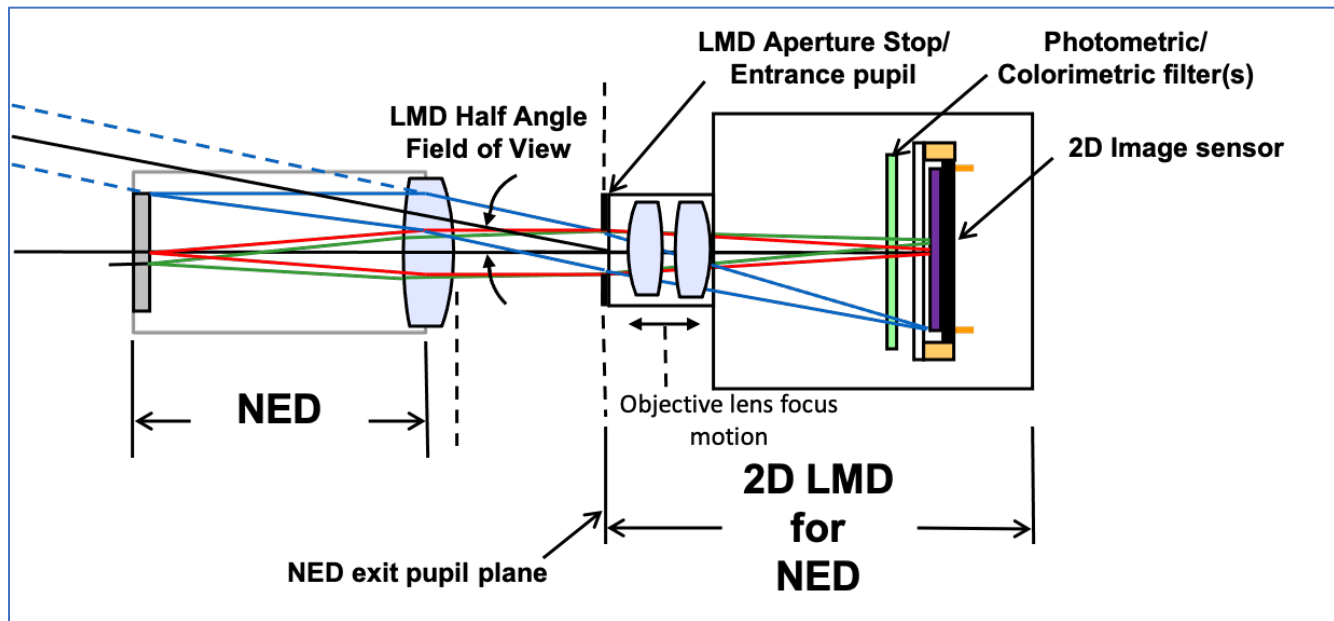


Fig. 8. A 2D LMD with the half angle field of view shown. A 2D LMD is required for Michaelson contrast and resolution measurements.



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19.3 EYE-POINT ALIGNMENT

DESCRIPTION: Experimentally determine the appropriate position to place the entrance pupil of an LMD for a near-eye display (NED) or a head-up display (HUD).

The NED or HUD optical design generally has an exit pupil (eyebow) where the viewer is expected to place their eye. The optimum view of the NED virtual image is then presumed to be at the center of the eyebow, called the eye-point. The entrance pupil of the human eye (the iris) should be centered at the eye-point position to evaluate the image quality of the NED. Therefore, the eye-point serves as an important reference position from which the NED should be characterized. Since the optical design of the NED predicts a specific eye-point position behind the NED, the manufacturer should define the eye-point position. However, the user is rarely given the eye-point position. In that case, it is necessary to experimentally estimate the eye-point position.

This section describes several methods that can be used to establish the eye-point position. In general, the entrance pupil of an LMD is moved through the 3D space behind the NED or HUD while measuring its virtual image. An attribute of the virtual image (such as luminance, contrast ratio, Michelson contrast, color, geometric distortion) is monitored as a means to find the boundary of the eyebow. A minimum threshold quality of each attribute is used to gauge when the entrance pupil still lies within the eyebow. The geometric center of this eyebow is then estimated as the eye-point.

APPLICATION: This measurement can be used for any NED or HUD. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs..

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR EYE-POINT ALIGNMENT

The alignment method can be used by a spot- type or 2D LMD (see 19.2).

- At least a 5-axis motion apparatus is needed to scan over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. It can also be helpful to use reference features on the fixture to position the DUT.
- The eye rotation vantage point method (19.5) is generally used to scan over the virtual image field of view. In that case, the entrance pupil is placed at the eye-point and the LMD is pivoted about a position 10 mm behind it (to simulate eye gaze). Alternatively, the pupil rotation vantage point method (19.5) can also be used to scan the virtual image field of view, but this method neglects the impact of eye gaze.
- The measurement distance between the NED or HUD and the LMD should be specified by the manufacturer. However, this is often not defined. If the eye relief is not specified, it will be assumed to be 25 mm (from the center of the last NED optical element to vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- For a spot-type LMD, the measurement field angle (aperture) is typically 2 degrees. When using the spot-type LMD, it is also useful that the LMD field of view be larger than the measurement field angle.
- When using a 2D LMD, the LMD should have a photopic response. The 2D LMD should have background, flat field, and geometric corrections applied.
- A rough visual alignment of the LMD can be made by placing the LMD entrance pupil at the approximate center of the light field projected behind the NED or HUD see Fig. 1.

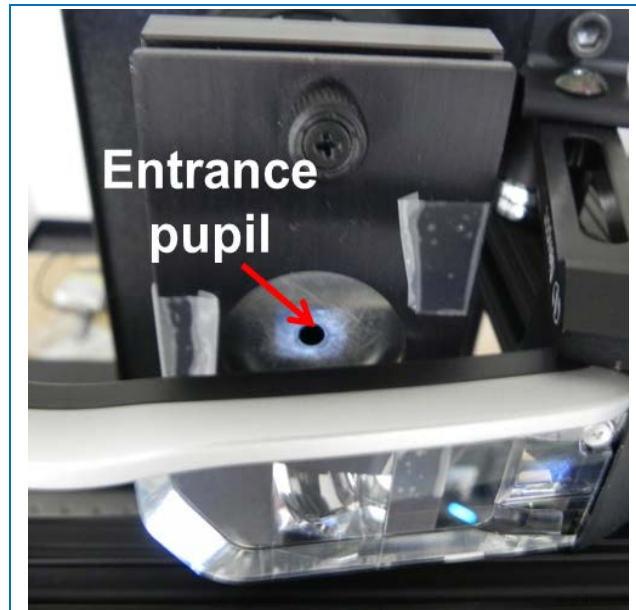


Fig. 1. Approximate entrance pupil alignment.

**PROCEDURE:**

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the eyepiece to be measured. If no measurement distance is specified for the NED, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis (z-axis) or eyeline.
2. Laterally position the LMD entrance pupil approximately in the center of the light field projected behind the NED or HUD (see Fig. 1).
3. Render an alignment target (such as a crosshair) at the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
4. Use the eye rotation vantage point method (19.5) to rotate the LMD field of view to the center of the virtual image.
5. Render the desired test pattern for the eye-point alignment. Possible test patterns include the crosshair, full-screen white, and grille patterns.
6. Laterally translate the LMD to the left while viewing the virtual image attributes (such as luminance, Michelson contrast, or virtual image field size). Determine the negative x-axis position of the LMD where the virtual image attribute achieves a desired threshold value.
7. Laterally translate the LMD to the right while viewing the same virtual image attribute. Determine the positive x-axis position of the LMD where the virtual image attribute achieves a desired threshold value.
8. Use the negative and positive x-axis boundary positions that produced the desired threshold value and calculate the x-axis mid-point position between those boundaries. Translate the LMD to that mid-point position and reset this as the new $x=0$ position.
9. Laterally translate the LMD up while viewing the same virtual image attribute. Determine the positive y-axis position of the LMD where the virtual image attribute achieves a desired threshold value.
10. Laterally translate the LMD down while viewing the same virtual image attribute. Determine the negative y-axis position of the LMD where the virtual image attribute achieves a desired threshold value.
11. Use the negative and positive y-axis boundary positions that produced the desired threshold value and calculate the y-axis mid-point position between those boundaries. Translate the LMD to that mid-point position and reset this as the new $y=0$ position.
12. Repeat steps 6 to 11 until the x-axis and y-axis mid-points are within 1 mm from the previous $x=y=0$ position (the origin for the current eyepiece).
13. Readjust the LMD focus as needed.
14. Record the absolute coordinates of the final eye-point position for the current eyepiece.

ANALYSIS: Depends on the attribute to be measured.

REPORTING: Report the absolute coordinates of the final eye-point position for the current eyepiece, the type of LMD, the setup conditions, the test pattern, the alignment method, the attribute and threshold value used to determine the eyebox boundaries.

COMMENTS:

The absolute position of the eye-point will be affected by the alignment method¹. The eye-point alignment method should be selected based on the most important characteristic needed for the application in which the NED or HUD is used.

REFERENCES:

¹R. S. Draper, J. Penczek, R. Varshneya, and P. A. Boynton, “Standardizing fundamental criteria for near eye display optical measurements: Determining eye-point position,” *SID Digest*, pp. 961-964, 30 May 2018.



19.3.1 EYE-POINT ALIGNMENT USING CROSSHAIR

ALIAS: Crosshair eye-point alignment

DESCRIPTION: Determine the eye-point position by using eyebox boundaries which start to vignette the center of the crosshair.

A white crosshair with a rectangular box at the edge of the virtual image is used as the test pattern (see Fig. 1a). The virtual image in the NED is monitored by an observer while the LMD is translated along the x and y axes. For this method, the boundary condition for defining the edge of the eyebox region is the point when one or more of three conditions occurs—1) the either the vertical or horizontal line width (for example full-width-at-half-maximum) for the cross hair image doubled in width, 2) the luminance of the line at the center dropped to half the peak value as estimated with a live view of the array camera line profile or 3) either the azimuth or elevation field coordinates of the crosshair intersection shifted in the array camera image by more than twice the original line width. Figure 1b illustrates the situation where the vertical line of the crosshair is about to fade in luminance as the LMD approaches the horizontal edge of the eyebox.

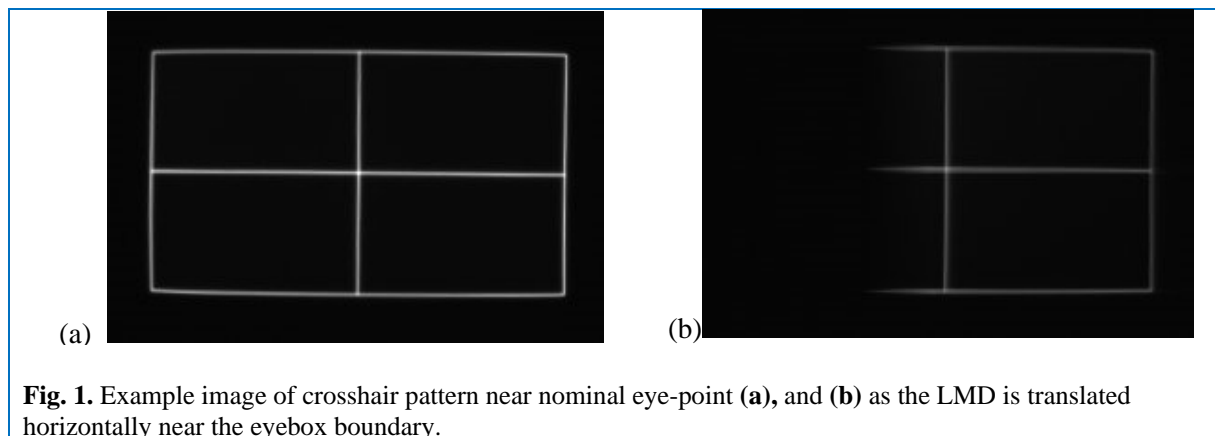
ADDITIONAL SETUP: The same setup conditions are used as the main section. A white crosshair test pattern through the center of the virtual image should be used (see Fig. 1). A 2D LMD is preferred for this method. The LMD should have enough resolution to clearly resolve change in the crosshair linewidth or a small position shift of the crosshair.

PROCEDURE: Same as main section. The evaluation of the crosshair can be made by a human observer. However, more reproducible results are expected by using an automated machine vision system.

ANALYSIS: Use camera vision software to evaluate the luminance of the crosshair lines, the width of the lines, and the amount of position shift of the crosshair as the LMD is translated through the eyebox.

REPORTING: Report the absolute coordinates of the final eye-point position for the current eyepiece, the type of LMD, the setup conditions, the test pattern, the alignment method, the attribute and threshold value used to determine the eyebox boundaries.

COMMENTS:





19.3.2 EYE-POINT ALIGNMENT BY CENTER LUMINANCE

ALIAS: Center luminance eye-point alignment

DESCRIPTION: Determine the eye-point position by using eyebox boundaries which cause a 50% reduction in the luminance at the center of the virtual image.

The LMD is aligned to the center of the virtual image and monitors the luminance of a full-screen white test pattern. The center luminance at the center of the virtual image is monitored as the LMD is translated along the x and y axes. The boundary of the eyebox is defined as the x and y axis positions that cause a 50 % reduction in the maximum luminance. The eye-point is then determined as the x and y axis mid-points for these boundaries.

ADDITIONAL SETUP: The same setup conditions are used as the main section. A full-screen white test pattern is used for this method. A spot-type or 2D LMD can be used for this method.

PROCEDURE: Same as main section. The LMD monitors the luminance at the center of the full-screen white virtual image. The LMD should use a 2 degree measurement field angle. A 50 % reduction from the maximum luminance determines the boundary of the eyebox.

ANALYSIS: The eye-point is determined as the x and y axis mid-points from the eyebox boundaries.

REPORTING: Report the absolute coordinates of the final eye-point position for the current eyepiece, the type of LMD, the setup conditions, the test pattern, the alignment method, the attribute and threshold value used to determine the eyebox boundaries.

19.3.3 EYE-POINT ALIGNMENT BY CENTER RESOLUTION

ALIAS: Center resolution eye-point alignment

DESCRIPTION: Determine the eye-point position by using eyebox boundaries which cause a 50% reduction in the Michelson contrast at the center of the virtual image.

The 2D LMD is aligned to the center of the virtual image and monitors the Michelson contrast of a white/black vertical and horizontal grille test pattern. The Michelson contrast is determined following the method in 7.2 and 19.5.4. A full screen 1x1 vertical and horizontal grille pattern is recommended. A lower spatial resolution grille pattern can be used if the 1x1 grille has a very low Michelson contrast. An example of a 1x1 vertical grille pattern near the nominal eye-point is shown in Fig. 1a. As the LMD is translated toward the eyebox boundary, the Michelson contrast is expected to drop (see Fig. 1b). Since the Michelson contrast can be different for the vertical and horizontal grille, the average Michelson contrast from the vertical and horizontal grille will be used for each eyebox position. The boundary of the eyebox is defined as the x and y axis positions that cause a 50 % reduction from the highest average Michelson contrast value. The eye-point is then determined as the x and y axis mid-points for these boundaries.

ADDITIONAL SETUP: The same setup conditions are used as the main section. A full-screen vertical and horizontal grille test pattern is used for this method. Alternatively, smaller patches of vertical and horizontal grilles grouped about the center of the virtual image can also be used. But the measurement ROI should be within 2.5 degrees of the center virtual image position. A 2D LMD should be used for this method.

PROCEDURE: Same as main section. At each eyebox position, the 2D LMD determines the average Michelson contrast between a 1x1 vertical grille and 1x1 horizontal grille at the center of the virtual image. The method in 7.2 is used to determine the Michelson contrast for each grille pattern. A 50 % reduction from the highest average Michelson contrast value determines the boundary of the eyebox.

ANALYSIS: The eye-point is determined as the x and y axis mid-points from the eyebox boundaries based on average Michelson contrast.

REPORTING: Report the absolute coordinates of the final eye-point position for the current eyepiece, the type of LMD, the setup conditions, the test pattern, the alignment method, the attribute and threshold value used to determine the eyebox boundaries.

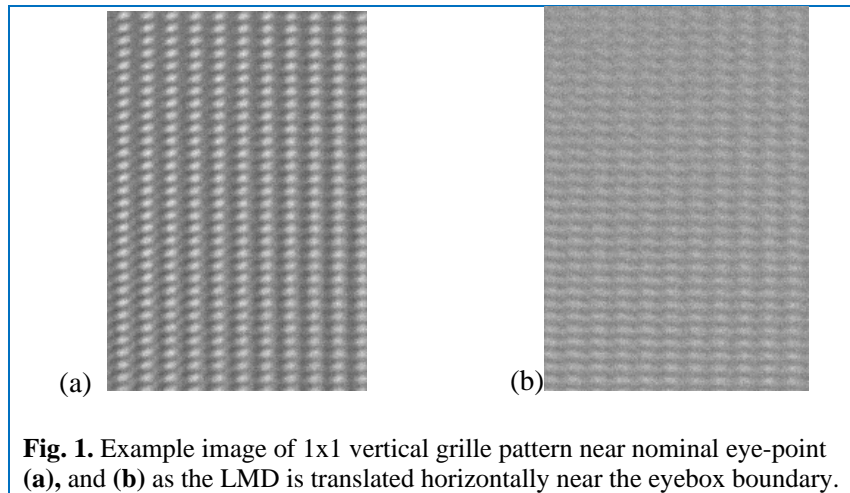


Fig. 1. Example image of 1x1 vertical grille pattern near nominal eye-point (a), and (b) as the LMD is translated horizontally near the eyebox boundary.

19.3.4 EYE-POINT ALIGNMENT BY FIELD OF VIEW

ALIAS: Field of view eye-point alignment

DESCRIPTION: Determine the eye-point position by using eyebox boundaries which reduce the virtual image field of view to 95 % of the unvignetted size.

A full-screen white test pattern is used to define the field of view (FOV) of the virtual image. The relative size of the virtual image FOV is determined by a 2D LMD with a FOV that is larger than the virtual image. A standard edge detection method can be used to determine the boundary of the image where the relative luminance is reduced to 50 % of the maximum luminance at each eyebox position. The relative size of the virtual image FOV can then be evaluated from the bounded area (see Fig. 1). The maximum virtual image FOV is presumed to be near the eye-point position. The initial placement of the LMD at the rough eye-point location (described in 19.3) is usually close enough to obtain the largest FOV image. But, if a nearby eyebox positions gives a larger FOV, this new eye-point position should be adopted. However, it should be noted that if the LMD is positioned far off the NED optical axis, optical aberrations may induce artificially larger FOV. A significant distortion of the virtual image shape may suggest off-axis aberrations.

The virtual image FOV is evaluated by edge detection while the 2D LMD is translated along the x and y axes. For this method, the eyebox boundary is defined as the LMD position where the virtual image FOV is reduced to 95 % of the unvignetted (maximum) FOV. Figure 2 illustrates the situation where the virtual image gets vignetted as the LMD passes through the horizontal edge of the eyebox.

ADDITIONAL SETUP: The same setup conditions are used as the main section. A full-screen white test pattern is used to define the relative FOV of the virtual image. A 2D LMD is used for this method. The 2D LMD should have a FOV larger than the virtual image FOV and have enough resolution for accurate edge detection and relative area determination. A 2D LMD with a smaller FOV may also be used, but the captured images of the virtual image FOV will need to be stitched together using the pupil rotation vantage point method.

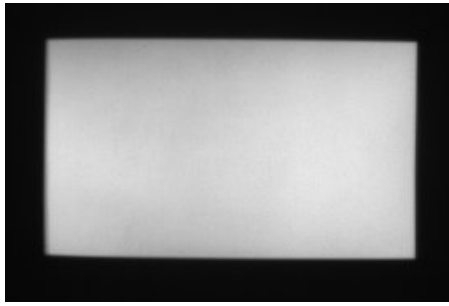
PROCEDURE: Same as main section. As the 2D LMD is translated through different eyebox positions, it determines the relative size of the virtual image FOV by edge detection of the full screen white test pattern. The boundary of the eyebox are determined when the virtual image FOV is reduced to 95 % of the unvignetted (maximum) FOV.

ANALYSIS: Use camera vision software for edge detection and determining the relative virtual image size as the LMD is translated through the eyebox.

REPORTING: Report the absolute coordinates of the final eye-point position for the current eyepiece, the type of LMD, the setup conditions, the test pattern, the alignment method, the attribute and threshold value used to determine the eyebox boundaries.



(a)



(b)

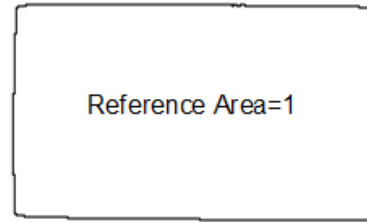
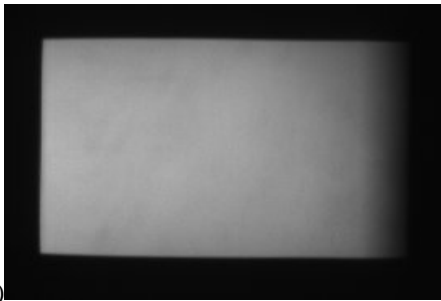


Fig. 1. Example image of unvignetted full-screen pattern near the nominal eye-point (a), and (b) the boundary area determined by edge detection.

(a)



(b)

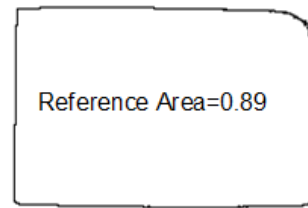


Fig. 2. Example image of vignetted full-screen pattern (a), and (b) the boundary area determined by edge detection.



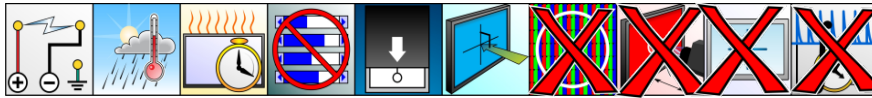
19.3.5 NED EYEBOX CENTERING TRANSVERSE CHROMATIC ABERRATIONS

ALIAS: eye-point, lateral chromatic aberration, chromatic distortion, lateral color

DESCRIPTION: The eye-point of a NED can be determined using the transverse chromatic aberrations (TCA) of the HMD. Transverse chromatic aberrations (TCA) are caused by the dispersion of the optics of the NED leading to a wavelength dependent magnification. TCA are minimized along the optical axis of the NED and can be used to determine the center of the eyebox. TCA is illustrated in Fig. 1a as an example. **Units:** none, **Symbol:** none

APPLICATION: This measurement has been applied to virtual reality NED that exhibit measurable TCA, such as wide field of view NED using Fresnel lenses. The method is intended to find the x,y eye-point location within the eyebox.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: This method uses a camera mounted on a three-axis stage to determine the eye-point position from the TCA. The TCA is measured using a fixed camera that images part or the full virtual image. TCA is measured using a pattern consisting of red, green, and blue bars one NED pixel wide displaced vertically by the height of the bar along the horizontal with a spacing of a few degrees in the field of view. The same pattern is used for the vertical direction, where the bars are displaced by the width of the bars in the horizontal direction (Fig. 1b)¹. The camera should have sufficient resolution to resolve the bars as well as subpixel pattern in the NED in order to measure shifts in the bars by one NED sub-pixel. After acquiring an image, the location of the minimum TCA in the image is determined, which is the eye-point of the eyebox. The camera can be moved to that location.²

PROCEDURE:

1. Set up the detector by aligning to NED with 25 mm eye relief + 3 mm to the LMD aperture stop of the entrance pupil.
2. Render a test pattern similar to the pattern shown in Fig. 1b on the NED.
3. Point the LMD viewfinder to center of the test pattern and set the point direction measurement angle to 0,0.
4. Acquire an image of the test pattern using the LMD.
5. Move LMD to a new x location in the eyebox.
6. Repeat steps 4 and 5 until $x = +2$ mm from the starting point.
7. Move the LMD back to the start position and repeat steps 4 through 6 in the opposite x direction.
8. Repeat steps 4 through 7 in the + y and - y directions.

ANALYSIS: This method requires determining the TCA for a particular x,y position of the camera in the eyebox and repeating the measurement for other x,y positions.

The TCA of the NED is calculated from the location of the center of the red, green, and blue bars on the camera. This can be accomplished by taking the horizontal and vertical profiles for each colored bar across the image. To improve the signal-to-noise and average over the subpixel pattern, it is recommended to sum NED 25 pixels in the direction perpendicular to the measurement direction. In other words, sum NED 25 pixels in the vertical direction when determining the horizontal TCA for each colored bar.

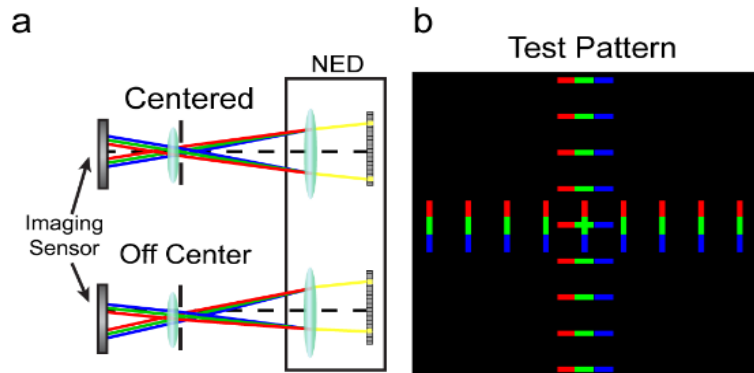


Fig. 1. a. Sketch of the setup for NED centered (top panel) and off center (bottom panel) in the eyebox. b. Example test pattern for TCA.



The position of the red and blue bars relative to the green bars can be calculated using

$$\Delta x'_{r/b} = x'_{r/b} - x'_g,$$

$$\Delta y'_{r/b} = y'_{r/b} - y'_g,$$

where $x'_{r,b,g}$ and $y'_{r,b,g}$ are the x' and y' positions of the red, blue, and green bars on the camera. This can be reported in pixels or converted to distance. By calculating the displacement relative to the green bars, the monochromatic aberrations, such as distortion are normalized out of the measurements. In addition, the position of the green bars can be used as the ideal bar position without TCA. The data for $\Delta x'_r$ versus x'_g and $\Delta x'_b$ versus x'_g are fit with lines and the intersection of the two lines gives the location of the minimum TCA on the camera, which is the eye-point. Figure 2 shows example data of the intersection point shifting depending on the location of the camera in the eyebox.

These measurements can be repeated for different x,y locations in the eyebox to create a map of the eyebox where the color scale is the offset of the TCA minimum from the center location. Figure 3 shows an example of the eyebox map for the horizontal and vertical directions.

REPORTING: Report the eye-point alignment method, the bar size and periodicity, method for determining the bar position, the raw angular dot positions, cross-section of the x and y directions of the TCA minimum across the eyebox.

COMMENTS:

This method is intended to be used with NED with measurable TCA. It has primarily been tested on Fresnel-type virtual reality head mounted displays. The method should be used after the first order alignment is complete and within a range of ± 2 mm in the x,y directions of the camera.

1. R. Beams, A. S. Kim, A. Badano "Transverse chromatic aberrations in virtual reality head-mounted displays" *Optics Express* **27**, 24877-24884 (2019).
2. R. Beams, A. S. Kim, and A. Badano. "Eyebox centering using chromatic aberrations of virtual reality head-mounted displays." *Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR)*. Vol. 11310. International Society for Optics and Photonics, 2020.

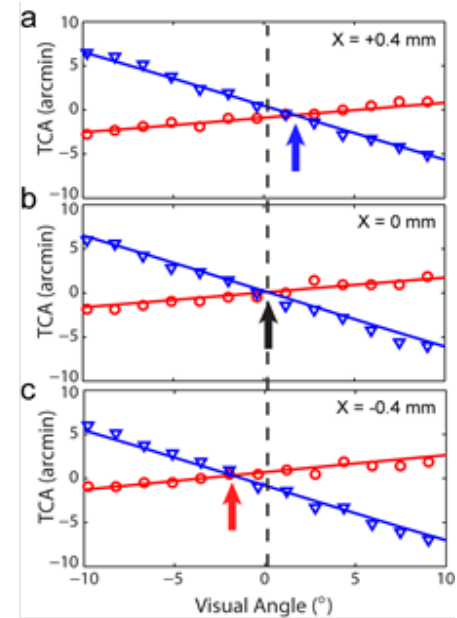


Fig. 2. TCA as a function of eyebox position with LMD displaced by a. 0.4 mm, b. 0 mm, and c. -0.4 mm in the horizontal direction.

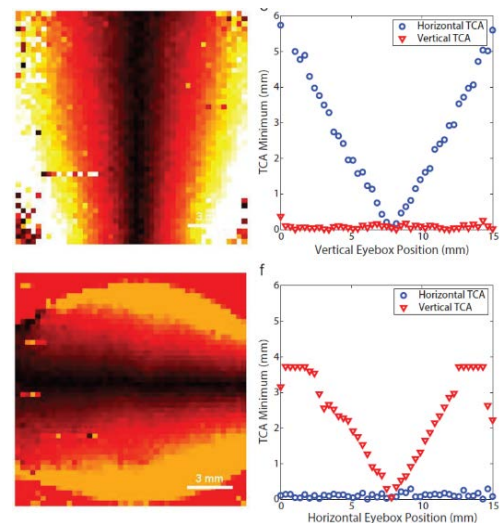


Fig. 3. Example plots of the eyebox in the horizontal (top row) direction and vertical direction (bottom row).



19.3.6 NED EYEBOX CENTERING USING COMA, ASTIGMATISM, FIELD CURVATURE

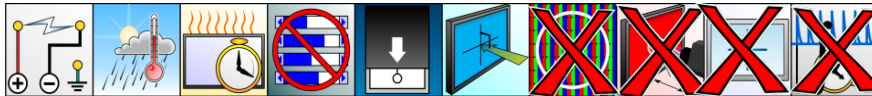
ALIAS: Eye-point, coma, astigmatism, field curvature

DESCRIPTION: This measurement has been applied to virtual reality NED that exhibit measurable optical aberrations that increase the size of dots in a test pattern and depend on their location in the image plane for the LMD, including coma, astigmatism, and field curvature.

APPLICATION: This method is particularly useful for wide field of view NED using Fresnel lenses. The method is intended to find the x,y location of the eye-point in the eyebox. It can be extended to find the camera position for best focus of the virtual image.

Units: unitless, fraction of image area above threshold, T **Symbol:** none

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: This method uses a camera mounted on a three-axis stage to determine the eye-point position from the optical aberration of the NED. Coma is used as an example. The aberrations are measured using a fixed camera that images the central part of the virtual image, with at least 4 camera pixels per NED pixel in order to resolve the subpixels on the NED. If the setup is not intended to resolve subpixels, then at least 4 camera pixels per dot on the NED is recommended. The test pattern should consist of a uniform pattern of one color of display subpixels (i.e., red, green, or blue) or a grid of single color dots space apart by at least 5 NED pixels in the center of the NED display. Green is recommended to minimize the TCA and simplify the interpretation. Figure 4 shows an example of the subpixel shapes at the eye-point and at 10° in the field of view. The comet-like shape of the green subpixels is characteristic of coma. The LMD is translated in x and y until the dot size in the central 2 degrees of the image on the LMD is minimized. The analysis method binarizes the images using a global threshold. After binarizing the images, the fraction of white pixels in the image provides a measure of the size of the dots in the image. The process is repeated for other x,y locations in the eyebox with the goal of minimizing the fraction, which indicates the dot size is minimized. This method should be used for the central ± 2 mm of the eyebox and not be used for first order alignment of the LMD to the NED.

PROCEDURE:

1. Set up the detector by aligning to NED with 25 mm eye relief + 3 mm to the LMD aperture stop of the entrance pupil.
2. Render a test pattern consisting of uniform green subpixels or small green circles spread apart by at least 5 NED pixels.
3. Point the LMD viewfinder to center of the test pattern and set the point direction measurement angle to 0,0.
4. Acquire the virtual image of the test pattern containing the 2-degrees of the center using the LMD.
5. Move LMD to a new x location in the eyebox
6. Repeat steps 4 and 5 until $x = + 2$ mm from the starting point
7. Move the LMD back to the start position and repeat steps 4 through 6 in the opposite x direction.
8. Repeat steps 4 through 7 in the + y and – y directions.

ANALYSIS:

1. Crop the image to the 2 degrees of the center of the LMD.
2. Normalize the image data by the maximum value.
3. Calculate the global threshold, T, using Otsu's method¹. The number of histogram bins should be set to the bit depth.
4. Binarize the image such that every pixel above or equal to T becomes white and below becomes black.
5. Calculate the fraction of pixels above T: fractional area = $N_w/(N_b+N_w)$, where N_w and N_b are the number of white and black pixels, respectively.
6. The minimum fractional area is the eye-point for the LMD. Example data in Fig. 5 was taken in the center of the eyebox and shifted by 2 mm horizontally are shown after step 5. The values from step 5 for different horizontal position in the eyebox are shown, where the minimum is shown at 0 mm.

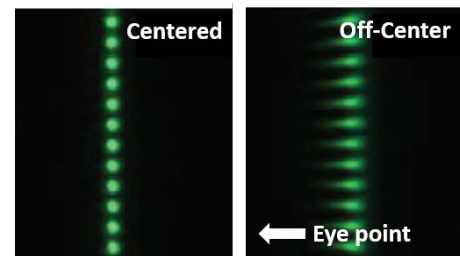


Fig. 4. Examples of the shape of green subpixels at the eye-point (left) and displaced in the eyebox showing coma.

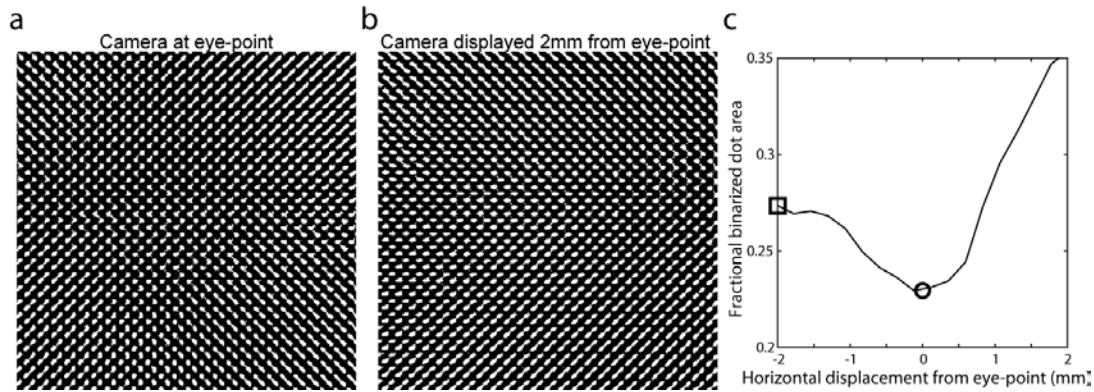


Fig. 5. a, b Examples images captured by the camera and binarized at the eye-point and displaced horizontally in the eyebox by 2 mm. The test pattern sent to the NED consisted of green sub-pixels. c. Plot of the fractional area of the image that are white pixels as a function of the camera displacement from the eye-point in the eyebox. The circle and the square symbols represent the fractional area for the images captured at the eye-point and displayed by 2 mm, as shown in a and b, respectively.

REPORTING: Report the eye-point alignment method, the test pattern used (including dot size and periodicity), plot of the binarized dot area as a function of the camera displacement.

COMMENTS:

This method is intended to be used with an NED that has measurable coma, astigmatism, or field curvature. It has primarily been tested on Fresnel-type virtual reality head mounted displays. The method should be used after the first order alignment is complete and within a range of ± 2 mm in the x,y directions of the camera.

1. Nobuyuki Otsu (1979). "A threshold selection method from gray-level histograms". IEEE Trans. Sys. Man. Cyber. **9** (1): 62–66



19.4 VIRTUAL IMAGE DISTANCE

ALIAS: focal distance

DESCRIPTION: Determine the distance to the virtual image displayed by a near-eye display (NED) for one eyepiece (either right eye or left eye location). This method can also be applied to HUD if there is a defined smaller eye motion volume for the left and right eye (such as limiting the span to within the nominal inter-pupillary distance of 65 mm) within the larger head motion eye box.

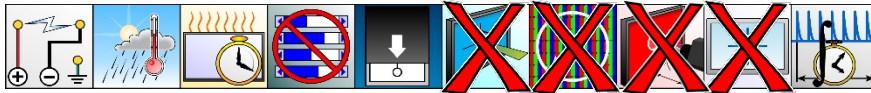
The NED or HUD optical design generally has an exit pupil (eye box) where the viewer is expected to place their eye to view the virtual image produced by the display. The focal distance necessary for a viewer to focus on the virtual image is the same as for a real object. The virtual image distance can change depending on the viewing direction of the eye and position of the pupil in the eye box.

This section describes two methods that can be used to measure the virtual image distance at the center of the virtual image field of view, and one method to measure the virtual image distance at different pointing directions within the NED field of view. For the first method, the entrance pupil of an LMD is moved laterally from the design eye-point and the angular shift of a feature in the virtual image is measured. Then using the lateral translation distance and the angular shift, the virtual image distance is calculated with trigonometry. The second method uses a focusable lens with an image distance read out on the focus adjustment mechanism of the LMD that is calibrated with equivalent real image distances.

19.4.1 Parallax Method

APPLICATION: This measurement can be used for any NED or HUD. These include freeform optics with OLED, LCOS and LED light engines, light field optics, waveguide optics and holographic optical element (HOE) NEDs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR VIRTUAL IMAGE DISTANCE

The virtual image distance method can use a spot-type LMD with a viewport or 2D LMD (see 19.2).

- At least a 4-axis motion apparatus is needed to scan over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. It can also be helpful to use reference features on the fixture to position the DUT.
- The measurement distance between the NED or HUD and the LMD entrance pupil is defined by the location of the eye-point (see 19.3).
- The position and size of the eye box are defined in section 19.9.
- For a spot-type LMD, the measurement field angle (aperture) is typically 2 degrees. When using the spot-type LMD, it is also useful that the LMD viewport field of view be larger than the measurement field angle.
- The 2D LMD should have background, flat field, and geometric corrections applied.
- The eye rotation vantage point method (19.5) is generally used to scan over the virtual image field of view. The pupil rotation vantage point method in 19.5 should be used for the parallax measurement at the center of virtual image. However, if the lateral translations used for the parallax measurements are kept small, then eye rotation and pupil rotation should give similar results. The vantage point method must be reported in the measurement results.

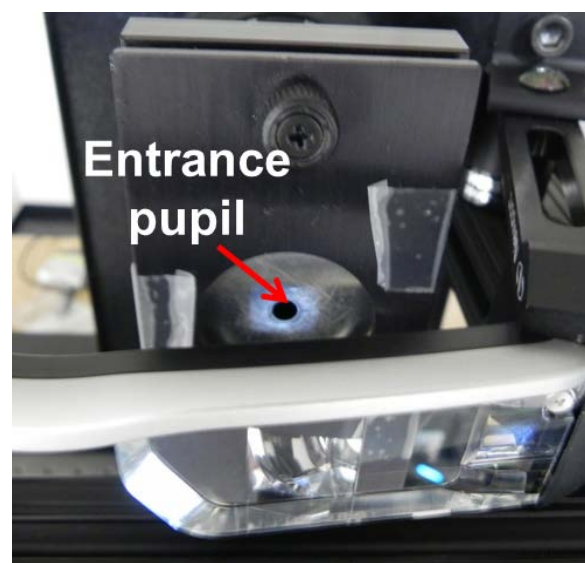


Fig. 1. Approximate entrance pupil alignment within the eye box.

PROCEDURE:

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the eyepiece to be measured (see Fig. 1). If no measurement distance is specified for the NED, place the entrance pupil of the LMD at the eye-point using the crosshair method as described in section 19.3.



2. Render a crosshair alignment target at the center of the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
3. Use the selected vantage point method (19.5) to rotate the center of the LMD field of view (FOV) to the center of the virtual image.
4. Record the horizontal position, D_0 , horizontal and vertical angle positions, ϕ_C and θ_C and assign this position and these angles a zero value (this is the origin).
5. Laterally translate the LMD to the left to the edge of the eye box (see 19.9).
6. Record the lateral motion distance to the left, D_L .
7. Rotate the center of the LMD FOV to the center of the virtual image.
8. Record the horizontal and vertical angle positions, ϕ_L and θ_L (note: the theta angles should be small).
9. Laterally translate the LMD back to the origin, D_0 position, and realign the LMD to the crosshair to minimize mechanical backlash.
10. The horizontal and vertical angles, ϕ_C and θ_C , should be within 0.01 degrees of the previous setting. Reset to zero if necessary. (Resetting to zero indicates that the mechanical translation mechanism lacks precise angle control and the reported virtual image distance results will have a higher uncertainty).
11. Laterally translate the LMD to the right to the edge of the eye box (see 19.9).
12. Record the lateral motion distance, D_R from the original center eye box position.
13. Rotate the center of the LMD FOV to the center of the virtual image.
14. Record the horizontal and vertical angle positions, ϕ_R and θ_R .
15. Calculate the virtual image distance using equation 1, where D_V is the virtual image distance, $D_T = (D_L + D_R)$ is the left to right distance traversed and $\phi = (|\phi_L| + |\phi_R|)$ is the horizontal angle measured between the left and right positions.

$$D_V = \left(\frac{D_L}{|\tan(\phi_L)|} + \frac{D_R}{|\tan(\phi_R)|} \right) / 2 \cong \frac{\frac{D_T}{2}}{\tan(\phi/2)} \quad (1)$$

The equation assumes that the theta and phi angles are small <3 degree.

Comment: If the mechanical system possibly has backlash transitioning from one side of the eye box to the other, the LMD should be realigned to the cross hairs and reset to zero before continuing to the other edge. The vertical change in angle from left to right should be less than 0.1 degree. If larger, repeat the rotational alignment to the DUT.

ANALYSIS: Calculate the virtual image distance using equation 1. The uncertainty of the measured virtual image distance is dependent on several factors including:

1. Total lateral distance between the left and right edge eye box measurement position points.
2. Limiting precision of the angular measurements.

Table 1 provides an example of the measurement error in the virtual image distance measurement shown for two different lateral distances across the eye box. Measurement error may be improved with more lateral measurement positions within the eye box.

Angular resolution of 12MP image sensor w/ 3.45 μm pixel size (degrees) = 0.004167

Angular precision of goniometer (robot) pointing direction (degrees) = 0.010

	Distance across the eye box D_T (meters)	0.010	0.020		0.010	0.020
True Virtual image distance (Diopters)	True Virtual image distance (meters)	Limiting resolution of reported value (meters)*	Limiting resolution of reported value (meters)*	*Based on the angular limiting resolution of:	% Limiting resolution of reported value	% Limiting resolution of reported value
0	Infinity	13750.987	13750.987	12MP image sensor	NA	NA
0.01	100	42.104	26.665	12MP image sensor	57.90	73.33
0.02	50	13.333	7.692	12MP image sensor	73.33	84.62
0.04	25	3.846	2.083	12MP image sensor	84.62	91.67
0.10	10	0.678	0.351	12MP image sensor	93.22	96.49
0.11	9	0.553	0.285	12MP image sensor	93.86	96.83



0.13	8	0.440	0.226	12MP image sensor	94.50	97.17
0.14	7	0.339	0.174	12MP image sensor	95.16	97.52
0.17	6	0.251	0.128	12MP image sensor	95.82	97.86
0.20	5	0.175	0.089	12MP image sensor	96.49	98.21
0.25	4	0.113	0.057	12MP image sensor	97.17	98.57
0.33	3	0.064	0.032	12MP image sensor	97.86	98.92
0.50	2	0.029	0.014	12MP image sensor	98.57	99.28
1.00	1	0.007	0.004	12MP image sensor	99.28	99.64

	Distance across the eye box D_T (meters)	0.010 m	0.020 m		0.010	0.020
True Virtual image distance Diopters	Virtual image distance True Value (meters)	Limiting resolution of reported value	Limiting resolution of reported value	*Based on the angular limiting resolution of:	% Limiting resolution of reported value	% Limiting resolution of reported value
1.11	0.9	1.392E-02	2.937E-03	goniometer (robot) pointing direction	98.45	99.67
1.25	0.8	1.102E-02	2.322E-03	goniometer (robot) pointing direction	98.62	99.71
1.43	0.7	8.451E-03	1.779E-03	goniometer (robot) pointing direction	98.79	99.75
1.67	0.6	6.220E-03	1.308E-03	goniometer (robot) pointing direction	98.96	99.78
2.00	0.5	4.327E-03	9.088E-04	goniometer (robot) pointing direction	99.13	99.82
2.50	0.4	2.775E-03	5.824E-04	goniometer (robot) pointing direction	99.31	99.85
3.33	0.3	1.564E-03	3.283E-04	goniometer (robot) pointing direction	99.48	99.89
5.00	0.2	6.974E-04	1.468E-04	goniometer (robot) pointing direction	99.65	99.93
10.00	0.1	1.760E-04	3.780E-05	goniometer (robot) pointing direction	99.82	99.96

REPORTING: Report the virtual image distance in meters and diopters, left edge and right edge eye box locations for the current eyepiece, resolution and precision of angular measurements, the type of LMD, the setup conditions.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Vantage-point method: Pupil rotation				
Measurement position	Distance to left side of eye box, D_L (m)	Left side horizontal Angle, ϕ_L (Deg.)	Distance to right side of eye box, D_R (m)	Right side horizontal Angle, ϕ_R (Deg.)
center	0.01	0.23	0.01	-0.24
Virtual image distance D_V (m)		$D_V = \left(\frac{D_L}{ \tan(\phi_L) } + \frac{D_R}{ \tan(\phi_R) } \right) / 2$		

COMMENTS:

The absolute position of the eye-point will be affected by the alignment method (see Section 19.3).



19.4.2 VIRTUAL IMAGE DISTANCE USING LMD LENS FOCUS

ALIAS: Calibrated focal distance lens measurement of virtual image distance.

DESCRIPTION: Determine the virtual image distance using an LMD configured with a focusing lens with a calibrated image distance scale.

A white/black vertical and horizontal line grille pattern is used as the test patterns (see Fig. 1a for vertical grille example). The virtual image in the NED is captured by a 2D LMD and monitored by an observer or by image processing software while the LMD lens focus is adjusted to a sharp focus setting.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR VIRTUAL IMAGE DISTANCE

The virtual image distance method can use a spot-type LMD with a viewport or 2D LMD (see 19.2).

- At least a 4-axis motion apparatus is needed to position the LMD relative to the NED device under test (DUT) over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. It can also be helpful to use reference features on the fixture to position the DUT.
- The measurement distance between the NED or HUD and the LMD entrance pupil is defined by the location of the eye-point (see 19.3).
- The position and size of the eye box are defined in section 19.9.
- When using the spot-type LMD, it is also necessary that the LMD viewport field of view be larger than the measurement field angle.
- The 2D LMD should have background, flat field, and geometric corrections applied.
- The eye rotation vantage point method (19.5) is generally used to scan over the virtual image field of view. The pupil rotation vantage point method in 19.5 may also be used for this virtual image distance measurement at the center of virtual image. Both vantage point methods should give identical or very similar results. The vantage point method must be reported in the measurement results.

ADDITIONAL SETUP: The same setup conditions are used as the section 19.3. A white crosshair test pattern through the center of the virtual image should be used to align the LMD to the center of the virtual image. A 2D LMD is preferred for this method. The grille pattern frequency chosen should provide Michelson contrast of at least 50% at the center of the virtual image.

PROCEDURE:

1. Align the LMD to the center of the virtual image. The region of interest (RIO) should be within ± 2.5 degrees of the center.
2. Display a vertical grille pattern (see Fig. 1) in the center of the virtual image.
3. Adjust the 2D LMD lens for best focus. The evaluation of the sharpness for best focus of the 2D LMD image can be made by a human observer. However, more reproducible results are expected by using an automated focus machine vision system. Record the virtual image distance f_V for the vertical grille pattern.
4. Display a horizontal grille pattern in the center of the virtual image.
5. Adjust the 2D LMD lens for best focus. Record the virtual image distance f_H for the horizontal grille pattern.

ANALYSIS: Compute the average virtual image focal distance: $f = (f_V + f_H)/2$ in meters.

REPORTING: Report the f , f_V , and f_H LMD lens focus distance settings for the current eyepiece, the type of LMD, the setup conditions, the test patterns and the alignment method.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Vantage-point method: Eye rotation		
Measurement position	f_v	f_H
center	1.42	1.48
Virtual image distance $f(m)$	1.45	

COMMENTS: The precision of the focus distance will depend on the distance and also the calibration of the lens focus distance reported by the manufacturer.

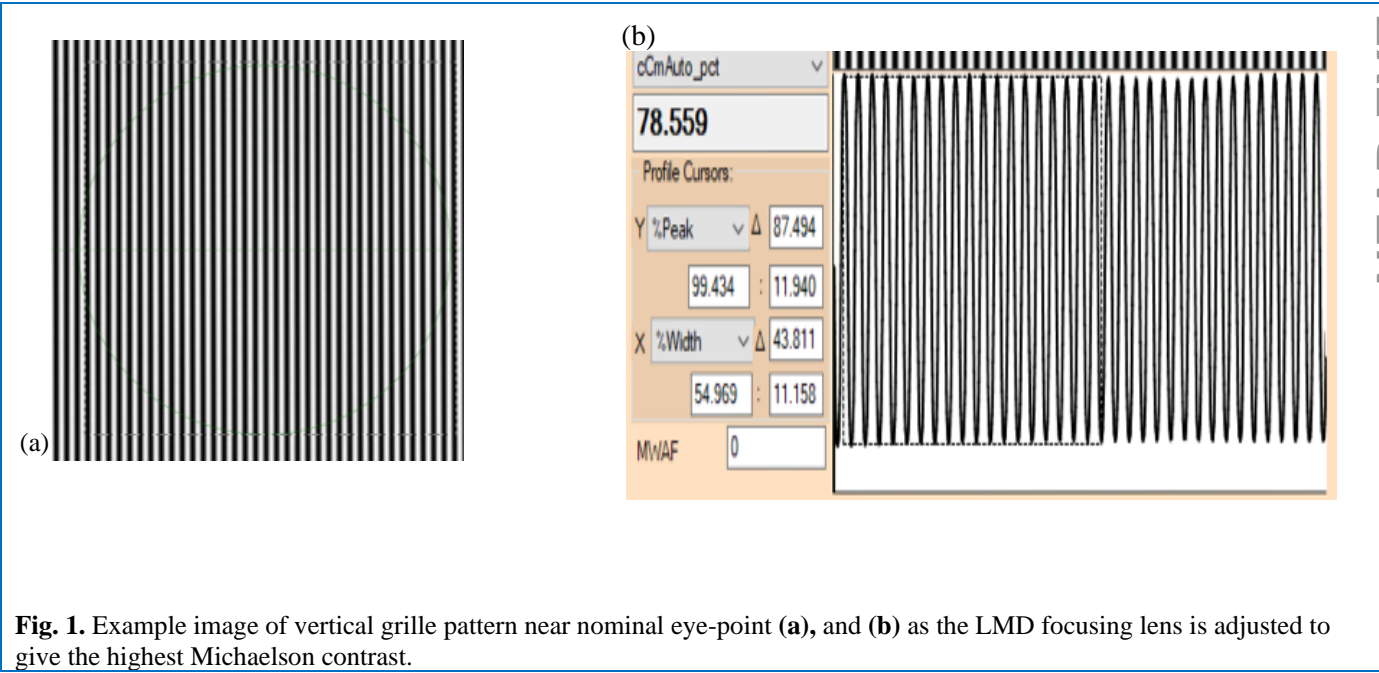


Fig. 1. Example image of vertical grille pattern near nominal eye-point (a), and (b) as the LMD focusing lens is adjusted to give the highest Michaelson contrast.



19.4.2.1 VIRTUAL IMAGE DISTANCE WITHIN THE FIELD OF VIEW

ALIAS: Virtual image distance mapping

DESCRIPTION: Determine the virtual image distance (VID) at different pointing directions within the virtual image field of view using an LMD configured with a focusing lens. The measurement points and alignment procedure are the same as defined in Section 19.5 for 5 pointing directions, 9 or more pointing directions

A white/black vertical and horizontal line grille pattern is used as the test patterns (see Fig. 1a in section 19.4.2 for vertical grille example). The virtual image in the NED is captured by a 2D LMD and the Michelson contrast is monitored and used as the focus criteria while the LMD lens focus is adjusted to a sharp focus setting.

ADDITIONAL SETUP: The same setup conditions are used as section 19.4.2. The grille pattern frequency chosen should provide a Michelson contrast of least 50% at the center of the virtual image and each of the other measured pointing directions.

PROCEDURE: There are two possible ways of performing this test. The one presented here has all the pointing directions measures for a single grille pattern and then repeated for the rotated grille pattern. An alternative is to change the grille pattern at each pointing direction before moving to the next pointing direction.

1. Align the LMD to the center of the virtual image. The region of interest (RIO) should be within ± 2.5 degrees of the center.
2. Display a vertical grille pattern (see Fig. 1) in the center of the virtual image.
3. Adjust the 2D LMD lens for best focus. The evaluation of the sharpness for best focus of the 2D LMD image can be made by a human observer. However, more reproducible results are expected by using an automated focus machine vision system. Record the virtual image distance f_V for the vertical grille pattern.
4. Change the pointing direction to center on position 1 shown in Fig. 1 and focus on the grille pattern. Record the virtual image distance f_V for the vertical grille pattern for this pointing direction.
5. Repeat step 4 for other pointing directions.
6. Display a horizontal grille pattern in the center of the virtual image and focus on the grille pattern. Record the virtual image distance f_H for the horizontal grille pattern at the center of the virtual image.
7. Change the pointing direction to center on position 1 shown in Fig. 1 and focus on the grille pattern. Record the virtual image distance f_H for the vertical grille pattern for this pointing direction.
8. Repeat step 7 for other pointing directions.

ANALYSIS: Compute the virtual image focal distance: $f = (f_{VA} + f_{HA})/2$ where $f_{VA} = (f_{V1} + f_{V2} + \dots + f_{VN})/N$ and $f_{HA} = (f_{H1} + f_{H2} + \dots + f_{HN})/N$. is determined from each of the different pointing directions within the FOV.

REPORTING: Report the absolute VID at each of the sampled pointing directions.

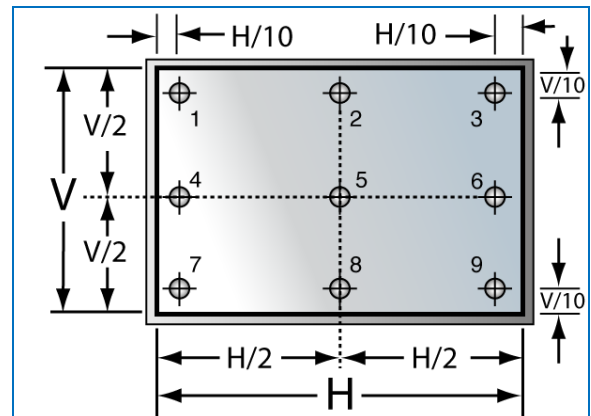


Fig. 1. Viewing positions in the virtual image from the eye point using 9 positions (locations 1 to 9), or 5 positions (locations 1,3,5, 7, and 9).

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Device description: NED1, left eye

Vantage-point method: Eye rotation		Test pattern: Vertical grille			Eye-point alignment method: Center by luminance
Measurement position	Virtual Image Distance	Measurement position	Virtual Image Distance	Measurement position	Virtual Image Distance
1	1.6	2	1.3	3	1.5
4	1.4	5	1.2	6	1.4
7	1.7	8	1.3	9	1.5
Average virtual image distance f_{VA} (m)		$(1.6+1.3+1.5+1.4+1.2+1.4+1.7+1.3+1.5)/9 = 1.433$ m add StandardDeviation			



NEAR EYE DISPLAYS

NEAR EYE DISPLAYS

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Device description: NED1, left eye					
Vantage-point method: Eye rotation		Test pattern: Horizontal grille			Eye-point alignment method: Center by luminance
Measurement position	Virtual Image Distance	Measurement position	Virtual Image Distance	Measurement position	Virtual Image Distance
1	1.6	2	1.3	3	1.5
4	1.4	5	1.2	6	1.4
7	1.7	8	1.3	9	1.5
Average virtual image distance f_{HA} (m)		$(1.6+1.3+1.5+1.4+1.2+1.4+1.7+1.3+1.5)/9= 1.433$ m add StandardDeviation			
virtual image distance f (m)		$(1.433 + 1.433)/2 = 1.433$			

COMMENTS: In some devices, the optical aberrations introduced in the virtual image can create false high Michelson contrast values substantially different from the focal distance at the center. The results over the FOV should be reviewed for gradual focal distance trends from the center of the virtual image, filtering out non-physical discontinuities. A possible diagnostic method is to reduce the spatial frequency of the grille pattern and confirm the repeatability the focus test results.



19.5 NED VANTAGE-POINT MEASUREMENTS

ALIAS: Viewing direction measurements

DESCRIPTION: Measure the viewing angle characteristics of a near eye display (NED) the way it is observed by a human user. That is by placing the entrance pupil (iris) at the center of the NED eyebox (eye point), then changing the viewing direction by rotating about the center of the eyeball, 10 mm behind the entrance pupil. This pivot point is called the eye rotation vantage-point (see 19.1) and serves as the reference viewing direction measurement method for NEDs. It is recommended that all vantage-point measurements use the eye rotation vantage-point method.

A pupil rotation vantage-point has also been used widely in industry. In this case, the measurements at various viewing directions are obtained by pivoting about the entrance pupil (see 19.1). This is typically employed when using a small entrance pupil with a wide field of view 2D LMD. Measurements taken by the pupil vantage-point method can sometimes correlate with the eye rotation vantage-point measurement results over narrow total field of view angles (<15 degrees). How much the pupil rotation measurements deviate from the eye rotation measurements will depend on the design characteristics of the NED, specifically the variation of results throughout the eye motion volume. Measurements taken with pupil rotation vantage-point geometry can only be presumed to correlate to the central 15 degrees. For larger viewing angles, it is possible to correlate the pupil rotation measurements from a particular NED device design to the reference eye rotation vantage-point measurements.

The general vantage-point is used to align the LMD to viewing directions in the virtual image in order to measure the desired physical attributes at those image positions. These image attributes can include luminance, chromaticity, contrast, color/chromaticity gamut, and others. The variation of these attributes with viewing direction also provides valuable uniformity information. The following procedure describes the process for measuring basic photometric and colorimetric measurements of a NED virtual image using the recommended eye point vantage-point measurement. The measurements are taken at specific viewing directions that are scaled to the virtual image being measured. The virtual image is assumed to be rectangular. At least the center of the virtual image is measured, although five or nine positions over the virtual image are often needed to represent the image uniformity. The results can produce a suite of metrics which can describe the NED's angular performance from the user's point of view, or vantage point. This suite of measurements strives to keep the viewer's perspective in mind.

The basic tables used in this section are contained in a visual performance reporting template at <https://doi.org/10.55410/xfsa8270>.

APPLICATION: This measurement can be used for any near-eye display. It has been shown to give reproducible and repeatable measurement results for a broad range of NED design technologies. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR VANTAGE-POINT MEASUREMENT

A spot-type LMD or 2D LMD according to 19.2 shall be used to measure the important characteristics of the NED virtual image. All evaluations are performed within a measurement field angle of ± 1 degree around the optical axis of the LMD. If another measurement field angle is used it shall be reported.

- The LMD needs to be aligned to the eye-point of the desired eyepiece. (See section 19.3)
- A goniometric motion apparatus is needed to scan over a range of viewing directions using the reference eye rotation vantage point method.
- The eye rotation vantage point method can be implemented by holding the NED in a fixed position and mounting the LMD on a precision positioning system or other device which allows for pivoting in azimuth and elevation about a central eye point. This allows for measurements of the desired positions in the virtual image field of the NED. Alternatively, the LMD can remain fixed, and the NED can be precisely positioned by pivoting about the same eye rotation vantage point.
- At least the center of the virtual image should be measured. For uniformity measurements, the five and nine positions illustrated in Fig. 1 are recommended. In the five position measurement case, the center point is number 5 and the corner points are 1, 3, 7, and 9, from upper left to bottom right.
- The eye-point position should be specified by the NED manufacturer. However, this is often not defined. If the eye relief is not specified, it will be assumed to be 25 mm along the NED optical axis (from the center of the last NED optic to the vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- Measurement field angle (aperture): 2 degrees, typical.



- In general, a full-screen test pattern of a single color should be used for relative luminance and chromaticity measurements. Absolute radiometric, photometric, and colorimetric measurements are typically measured at least in the center of the virtual image. If the luminance and color characteristics of the device are unknown, then the Multicolor pattern with 25 % pre-gamma Average Picture level (APL) should be used (see 5.4). The luminance of some display technologies can depend on the amount of content (APL level) rendered in the virtual image. This can be checked by measuring the center luminance of an increasingly larger white box in the center of the image. If the luminance is found to depend on the APL level, then absolute radiometric, photometric, and colorimetric measurements of the desired color should be taken with the Multicolor pattern at an APL level appropriate for the intended application, otherwise use the standard 25 % APL level. If it can be shown that the center measurement using full-screen color patterns give equivalent results to using a Multicolor pattern, then a full-screen pattern can be used for absolute measurements.

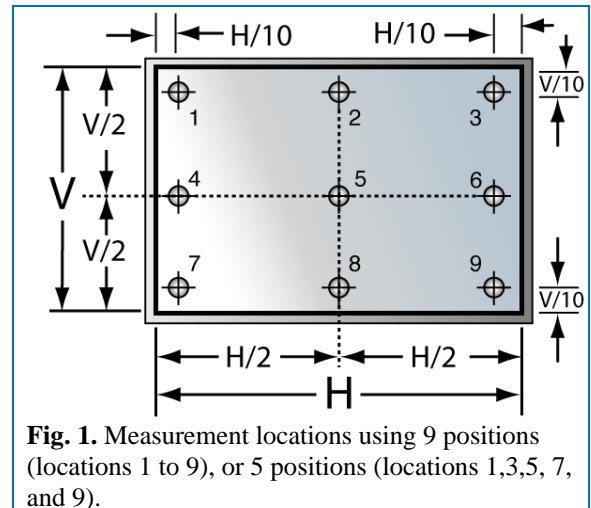


Fig. 1. Measurement locations using 9 positions (locations 1 to 9), or 5 positions (locations 1,3,5, 7, and 9).

PROCEDURE:

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis or eyeline.
2. Laterally position the LMD entrance pupil in the center of the eyebox, as specified by the manufacturer. If that position is not specified, use one of the eye point alignment methods in 19.3 to locate the eye-point and align the LMD to the center of the virtual image. Adjust the LMD for best focus at the center of the virtual image. This eye-point is the reference measurement location and is assumed to be roughly near the center of the NED eyebox.
3. Render an alignment target (such as in Fig. 1) as the virtual image to identify the locations to be measured. The eye rotation vantage-point method is used to align the LMD (or NED device) to the appropriate measurement locations in the virtual image. The LMD alignment of each virtual image location can be recorded for future measurements, or the alignment pattern can be presented for aligning the LMD prior to each measurement. The five or nine virtual image positions illustrated in Fig. 1 are recommended, assuming the virtual image is rectangular. Additional virtual image locations can be measured, but at least the center of the virtual image should be measured.
4. For absolute radiometric, photometric, and colorimetric measurements, align the LMD to the center of the virtual image. Render the multicolor pattern at 25 % APL with the desired center color (see 5.4) in the virtual image. A full-screen pattern may also be used if it can be shown that it produces equivalent results to the multicolor pattern. For relative luminance and chromaticity measurements, a full-screen pattern using a single color should be rendered in the virtual image.
5. Measure all the desired NED attributes (typically at least the luminance and chromaticity) for a given test pattern. The absolute spectral radiance, luminance, and chromaticity should be measured at least in the center of the virtual image. And uniformity should be measured at each of the standard locations in the virtual image (see Fig. 1). Assure that the measurement field at the larger viewing directions at the corners does not extend beyond the edge of the virtual image boundary. The edge of the measurement field should be at least 0.5° from the edges of the virtual image boundary. Measurements on the following performance attributes are recommended:
 - a. Center luminance and luminance uniformity for red, green, blue, white, and black.
 - b. Center white CCT
 - c. Center chromaticity and chromaticity uniformity for red, green, blue, and white.
 - d. Center contrast ratio and contrast ratio uniformity
 - e. Optional measurements for all positions:
 - Luminance and chromaticity with grayscale
 - Red, Green, and Blue luminance and chromaticity versus code value
 - Luminance and chromaticity of R, G, B, and W with ambient illumination
6. Readjust the LMD focus as needed at each virtual image position in the visual field.
7. The results can be reported as illustrated by the table below.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Device description: NED1, left eye

Vantage-point method: Eye rotation						Test pattern: Full screen					Eye-point alignment method: Center by luminance					
Measurement position		White				Black		Red			Green			Blue		
Point	Position	L_W	u'	v'	CCT^\dagger	L_K	C.R.*	L_R	u'_R	v'_R	L_G	u'_G	v'_G	L_B	u'_B	v'_B
1	U.L.[1]	100.80	0.2043	0.486	5287	0.421	239.5	25.65	0.3889	0.5289	68.55	0.1289	0.5621	8.55	0.154	0.2100
2	U.R.[3]	109.80	0.1936	0.5007	5308	0.3803	288.72	27.47	0.4107	0.5324	75.02	0.1214	0.5663	9.04	0.1462	0.2323
3	Center[5]	243.40	0.1958	0.4844	5806	0.37	657.84	58.22	0.4243	0.5323	164.40	0.1259	0.5630	20.72	0.1519	0.2028
4	L.L.[7]	111.90	0.1932	0.4998	5352	0.392	285.5	28.49	0.4086	0.5322	75.98	0.1203	0.5658	9.39	0.1463	0.2327
5	L.R.[9]	103.80	0.2033	0.4870	5318	0.403	257.56	25.99	0.4304	0.5290	71.20	0.1291	0.5625	8.66	0.1551	0.2082
Maximum		243.4			5806	0.421	657.84	58.22			164.4			20.72		
Minimum		100.8			5287	0.37	239.5	25.65			68.55			8.55		

† See B1.2.1.

* Calculated value: L_W/L_K

[1] U.L. = Upper left measurement point

[2] U.R. = Upper right measurement point

[3] Center = Center of virtual image, normal to the virtual image (aligned with the NED optical axis) -- used as the reference for all other off-angle measurements.

[4] L.L. = Lower left measurement point

[5] L.R. = Lower right measurement point

In this example table, the CIE 1976 chromaticity coordinates are reported. However, the CIE 1931 chromaticity coordinates may also be used.

ANALYSIS:

A variety of performance metrics can be determined from the measurement data summarized in the above table.

- The white point of the NED can be represented by a correlated color temperature (CCT) following the method in B1.2.1.
- The sampled luminance and contrast ratio nonuniformity are often expressed in term of the minimum and maximum values measured over the image, and have the following form:

$$N = 100\% \left[\frac{\max - \min}{\max} \right] \quad (1)$$

- The chromaticity difference $\Delta u'v'$ between any two colors can be expressed as the Euclidean distance between their chromaticity coordinates in the CIE 1976 chromaticity diagram using the following expression:

$$(\Delta u'v')_{ij} = \sqrt{(u'_i - u'_j)^2 + (v'_i - v'_j)^2} \quad (2)$$

where i and j represent the i th and j th colors, with $i \neq j$, in a series of chromaticity measurements. The chromaticity nonuniformity over an image of a single color can be expressed as the largest chromaticity difference $\Delta u'v'$ between any two measured colors in the image.

- A simple metric for representing the color range of the NED is the chromaticity gamut area. It is determined by measuring the CIE 1931 or 1976 chromaticity coordinates of the RGB primaries at maximum signal level. The gamut area enclosed by the RGB primary triangle for the CIE 1931 (GA_{xy}) and CIE 1976 ($GA_{u'v'}$) chromaticity diagram relative to the entire spectrum locus is determined by the following equations:

$$GA_{xy} = 149.6 |(x_R - x_B)(y_G - y_B) - (x_G - x_B)(y_R - y_B)| \quad (3)$$



$$GA_{u'v'} = 256.1 \left| (u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B) \right| \quad (4)$$

where the subscripts R, G and B refer to the red, green, and blue primaries, respectively.

CAUTION: The chromaticity gamut area presumes that the device exhibits luminance additivity. That is, it assumes that color-signal white luminance will equal the full-screen white luminance (see 5.4). If the device does not exhibit additivity, then the advanced color metric should be used to evaluate the color range of the device, such as the CIELAB color gamut volume.

REPORTING: From the measured results calculate the performance per the table.

COMMENTS:

1. **Number of points:** This test suite can be done for 5 points, 9 points (3 x 3), or higher number of points as needed. The measured values can vary widely across the virtual image field relative to the center of the virtual image, so there may be a need to measure more points for uniformity measurements.
2. **Measurement distance:** If a less than or equal to 28 mm measurement is not achievable for a NED LMD due to size of the aperture mounting or lens size, then it is not possible to use that particular NED LMD.
3. **Detector mount geometrical center:** The mounting mechanism for the detector and the detector attachment position to the mount with respect to the lens entrance pupil position must assure that the pivoting of the entrance pupil is at one of two allowed positions. The preferred choice for the pivot point is 10 mm behind the entrance pupil and along the optical axis of the detector (eye rotation vantage point). The other is in the plane of the entrance pupil of the LMD (pupil rotation vantage point). The selected vantage point must be reported since the measurement results will be different for the two vantage points.
4. Normally in display angle measurements, the LMD is fixed to measure only the center of the display and the display moves about the center to the offset angles to be measured. Many measurements with that method could result in a viewing cone emanating from the center. In this test method, the display remains fixed, and the LMD changes direction to look about the extremities of the display. For these measurements, the measurement distance changes for each point measured. This may be visualized as an inverse of the viewing cone, where the center of the cone is where the display would be viewed by eye and the cone spreads as it nears the display virtual image.



—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Reporting example					
Parameter	Color	Value	Specification	Values	Pass/Fail
Eye relief (remember 3 mm Cornea offset)	N/A	25 mm	25 mm		
Measurement field angle	N/A	2-degree	2-degree		
Chromaticity Nonuniformity ($\Delta u'v'$) _{max}	White	0.01636		$\Delta u'v'$ maximum	
Red	0.01570				
Green	0.00623				
Blue	0.03043				
Black					
Luminance Nonuniformity (%)	White	51.3384		% maximum	
Red	55.3240				
Green	50.2482				
Blue	79.4624				
Black	12.1				
Contrast Ratio Nonuniformity (%)	White/Black	63.6		% maximum	
CIE 1931 Color Gamut (GA_{xy})	Gamut calc.	65.0538		Min. gamut	
CIE 1976 Color Gamut ($GA_{u'v'}$)	Gamut calc.	97.6		Min. gamut	
Center Contrast Ratio	L_W / L_B	265.0539		Min. contrast	
CCT Nonuniformity (%)	White	8.9390		% maximum	
Supplemental Reporting Example					
Horizontal pixels (N_H)	3200				
Vertical pixels (N_V)	1800				
Image width (H - Angle of the active area)	32	degrees			
Image height (V - Angle of the active area)	18	degrees			
Diagonal angle in degrees (D)	36.72	degrees			
Aspect Ratio	16:9				
	Point 1 U.L.[1]	Point 2 U.R.[3]	Point 3 Center[5]	Point 4 L.L.[7]	Point 5 L.R.[9]
Elevation (θ) - degrees	7.5	7.5	0.000	-7.5	-7.5
Azimuth (ϕ) - degrees	-30.5	30.5	0.000	-30.5	30.5
Focal distance at measurement points (Diopters)	1	1	1	1	1



19.5.1 CENTER VIRTUAL IMAGE BASIC MEASUREMENTS

DESCRIPTION: Measure the center luminance, chromaticity, white CCT, contrast ratio, and chromaticity gamut area of the NED virtual image for the primary colors (RGB), white, and black. **Units:** various; and **Symbol:** various.

Absolute center photometric and colorimetric measurements are performed using the multicolor test pattern at a 25 % APL level. Unless stated otherwise, the luminance of white and the primary colors will be measured by supplying the display with the maximum signal for the R, G and B input channels.

ADDITIONAL SETUP: The same setup conditions are used as the main section.

PROCEDURE: Same as main section.

ANALYSIS: Same as main section.

REPORTING: Report values of all measured colors. See example template below.

—SAMPLE DATA ONLY—						
Do not use any values shown to represent expected results of your measurements.						
ICDM Center of Virtual image Basic Measurements Reporting Sheet (Darkroom Measurements)						
Primary	L (cd/m ²) (5.3)	x (5.14)	y (5.14)	CCT (B1.2.1)	C.R. (5.9)	Gamut (19.4, et al)
White	243.40	0.3373	0.3567	5806		
Red	58.22	0.6334	0.3532			31.6
Green	164.40	0.3024	0.6009			
Blue	20.72	0.1414	0.0839			
Black	0.37	0.3373	0.3567	5806	657.8	

$$C = L_w / L_k$$

Color code:

 = Measurement results
 = Calculated values



19.5.2 LUMINANCE AND CONTRAST RATIO UNIFORMITY

DESCRIPTION: Measure the luminance and contrast ratio nonuniformity of the NED virtual image. **Units:** none; and **Symbol:** N .

Luminance uniformity measurements use a full-screen single color test pattern. Unless stated otherwise, the luminance of white and the primary colors will be measured by supplying the display with the maximum signal for the R, G and B input channels (similar to 5.3 and 5.14).

ADDITIONAL SETUP: The same setup conditions are used as the main section.

PROCEDURE: Same as main section.

ANALYSIS: The contrast and luminance percent nonuniformity follows the general form in 8.1:

REPORTING: Report contrast ratio and the luminance values of all measured colors. See example templates for contrast ratio and uniformity reporting below.

—SAMPLE DATA ONLY—							
Do not use any values shown to represent expected results of your measurements.							
Luminance and Contrast Ratio Uniformity Reporting Sheet (Darkroom Measurements)							
Device description: NED1, left eye							
Vantage-point method: Eye rotation		Test pattern: Full screen				Eye-point alignment method: Center by luminance	
Measurement position		White	Red	Green	Blue	Black	Contrast Ratio
9 pt.	5 pt.	L_W (cd/m ²)	L_R (cd/m ²)	L_G (cd/m ²)	L_B (cd/m ²)	L_K (cd/m ²)	C.R. (L_W / L_K)
1	1	100.80	25.65	68.55	8.55	0.421	239.5
2							
3	3	109.80	27.47	75.02	9.04	0.3803	288.72
4							
5	5	243.40	58.22	164.40	20.72	0.37	657.84
6							
7	7	111.90	28.49	75.98	9.39	0.392	285.5
8							
9	9	103.80	25.99	71.20	8.66	0.403	257.56
Ave		133.94	33.164	91.03	11.272	0.39326	345.824
Min		100.80	25.65	68.55	8.55	0.37	239.5
Max		243.40	58.22	164.40	20.72	0.421	657.84
Percent nonuniformity (8.1)		58.6	55.9	58.3	58.7	12.1	63.6

19.5.3 CHROMATICITY UNIFORMITY

DESCRIPTION: Measure the chromaticity nonuniformity of the NED virtual image. **Units:** none; and **Symbol:** $(\Delta u'v')_{\max}$.

Chromaticity nonuniformity measurements use a full-screen single color test pattern. Unless stated otherwise, the luminance of white and the primary colors will be measured by supplying the display with the maximum signal for the R, G and B input channels (similar to 5.3 and 5.14).

ADDITIONAL SETUP: The same setup conditions are used as the main section.

PROCEDURE: Same as main section.

ANALYSIS: See main section.

REPORTING: Report chromaticity values of all measured colors. See example templates for chromaticity uniformity reporting below.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Chromaticity Uniformity Reporting Sheet
(Darkroom Measurements)

Device description: NED1, left eye

Vantage-point method: Eye rotation		Test pattern: Full screen						Eye-point alignment method: Center by luminance			
Measurement position		White		Red		Green		Blue		Black	
9 pt.	5 pt.	u'	v'	u'	v'	u'	v'	u'	v'	u'	v'
1	1	0.2043	0.486	0.3889	0.5289	0.1289	0.5621	0.154	0.2100	0.2043	0.486
2											
3	3	0.1936	0.5007	0.4107	0.5324	0.1214	0.5663	0.1462	0.2323	0.1936	0.5007
4											
5	5	0.1958	0.4844	0.4243	0.5323	0.1259	0.5630	0.1519	0.2028	0.1958	0.4844
6											
7	7	0.1932	0.4998	0.4086	0.5322	0.1203	0.5658	0.1463	0.2327	0.1932	0.4998
8											
9	9	0.2033	0.4870	0.4304	0.5290	0.1291	0.5625	0.1551	0.2082	0.2033	0.4870

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

White Chromaticity Nonuniformity Reporting Sheet
(Darkroom Measurements)

Device description: NED1, left eye

Vantage-point method: Eye rotation				Test pattern: Full screen				Eye-point alignment method: Center by luminance				
Measuring point		White $\Delta u'v'$										
9 pt.	5 pt.	u'_1	v'_1	1	2	3	4	5	6	7	8	9
1	1	0.2043	0.4860									
2												
3	3	0.1936	0.5007	0.0182								
4												
5	5	0.1958	0.4844	0.0086		0.0164						
6												
7	7	0.1932	0.4998	0.0010		0.0010		0.0156				
8												
9	9	0.2033	0.4870	0.0168		0.0168		0.0079		0.0163		
Result: $(\Delta u'v')_{\max} = 0.0182$												



19.5.4 MICHELSON CONTRAST UNIFORMITY

ALIAS: Grille contrast

DESCRIPTION: Measure the Michelson contrast of the NED virtual image under dark room conditions. **Units:** none; and **Symbol:** C_M .

The Michelson contrast of a white and black grille pattern rendered in the virtual image is generally measured following the method in 7.2. The setup conditions are similar to those in 19.11.2, but the virtual image is measured in this case (under darkroom conditions). The center of the virtual image is used to measure the reference Michelson contrast value for a vertical and horizontal grille pattern, usually at the highest resolution that the NED is capable of rendering. The Michelson contrast can also be measured at several spatial frequencies below its native resolution. Since the Michelson contrast can vary over the virtual image field of view, it is also valuable to measure the nonuniformity of the Michelson contrast over that field using the eye rotation vantage point method.

ADDITIONAL SETUP: A 2D imaging LMD is used to capture the grille pattern rendered by the NED. The LMD should be calibrated to give luminance images. The same setup conditions are used as the main section to align the LMD to the NED, but the test pattern to be measured will be a vertical and horizontal grille pattern. A full-screen vertical or horizontal grille pattern can be used to measure the Michelson contrast at the center, 5 positions, or 9 positions in the virtual field defined in 19.5. Alternatively, smaller patches of vertical and horizontal grilles centers about the standard measurement positions can also be used. But the measurement ROI should be within ± 2.5 degrees about the standard measurement positions defined in 19.5.

PROCEDURE:

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis or eyeline.
2. Laterally position the LMD entrance pupil in the center of the eyebox, as specified by the manufacturer. If that position is not specified, use one of the eye point alignment methods in 19.3 to locate the eye-point and align the LMD to the center of the virtual image. Adjust the LMD for best focus at the center of the virtual image. This eye-point is the reference measurement location and is assumed to be roughly near the center of the NED eyebox.
3. Render an alignment target (such as in Fig. 1) as the virtual image to identify the locations to be measured. The eye rotation vantage-point method is used to align the LMD (or NED device) to the appropriate measurement locations in the virtual image. The LMD alignment of each virtual image location can be recorded for future measurements, or the alignment pattern can be presented for aligning the LMD prior to each measurement. The five or nine virtual image positions illustrated in Fig. 1 are recommended, assuming the virtual image is rectangular. Additional virtual image locations can be measured, but at least the center of the virtual image should be measured.
4. Render a vertical white/black grille pattern over the full screen at the highest spatial resolution of the NED. See 19.11.2 to confirm that the 2D LMD has sufficient resolution to measure the NED resolution.
5. Use the eye rotation vantage point method to align the center of the 2D LMD to the first location of the standard virtual image positions defined in 19.5.
6. Acquire the relative luminance image of the grille pattern. Use the analysis method described in 7.2 to evaluate the Michelson contrast. The ROI for the analysis should be within ± 2.5 degrees about the standard virtual image position being measured.
7. Repeat steps 5 and 6 for all remaining standard virtual image positions using the eye rotation vantage point method. Readjust the LMD focus as needed at each virtual image position in the visual field.
8. Render a horizontal grill pattern at the same spatial resolution of the NED. Repeat steps 5 to 7 for all the desired standard measuring positions.

ANALYSIS:

The Michelson contrast is determined from the acquired images at all the standard virtual image positions by following the method in 7.2, with additional guidance in 19.11.2. The Michelson contrast is defined as:

$$C_M = \frac{L_W - L_K}{L_W + L_K} \quad (1)$$

where L_W and L_K are the average maximum white luminance and average minimum black luminance (minus glare correction), respectively, of the grille pattern. The Michelson contrast nonuniformity N_{MC} over the virtual image is defined by:



$$N_{MC} = 100\% \left[\frac{C_{Mmax} - C_{Mmin}}{C_{Mmax}} \right]$$

(2)

where C_{Mmax} is the maximum Michelson contrast and C_{Mmin} is the minimum Michelson contrast in the virtual image.

REPORTING: Report all of the Michelson contrast values measured at the standard virtual image positions. See example template for Michelson contrast and uniformity reporting below.

NEAR EYE DISPLAYS

NEAR EYE DISPLAYS

—SAMPLE DATA ONLY—								
Do not use any values shown to represent expected results of your measurements.								
Michelson contrast Uniformity Reporting Sheet								
(Darkroom Measurements)								
Device description: NED1, left eye								
Vantage-point method: Eye rotation		Test pattern: Full screen Vertical and Horizontal Grille			Eye-point alignment method: Center by luminance			
Measurement position		Vertical Grille White	Vertical Grille Black	Vertical Grille Michelson contrast	Horizontal Grille White	Horizontal Grille Black	Horizontal Grille Michelson contrast	Focal Distance
9 pt.	5 pt.	L_W (cd/m ²)	L_K (cd/m ²)	C_M	L_W (cd/m ²)	L_K (cd/m ²)	C_M	(Diopter)
1	1	100.80	43.2	0.400	101.2	42.8	0.406	1
2								
3	3	109.80	33.2	0.536	110.0	32.6	0.543	1
4								
5	5	243.40	35.3	0.747	245	36.3	0.742	1
6								
7	7	111.90	32.6	0.549	112.3	33.2	0.544	1
8								
9	9	103.80	41.3	0.431	102.2	41.6	0.421	1
Ave				0.532			0.531	
Min				0.400			0.406	
Max				0.747			0.742	
Percent nonuniformity				46.4%			45.3%	



19.5.5 CHROMATICITY GAMUT AREA UNIFORMITY

ALIAS: gamut area uniformity

DESCRIPTION: Measure the CIE 1931 chromaticity gamut area uniformity of the NED virtual image. **Units:** none; and

Symbol: $N_{G_{Axy}}$.

The NED CIE 1931 chromaticity gamut area is best represented by a measurement in the center of the virtual image using the multicolor test pattern at a 25 % APL level (see 19.5.1). However, this pattern is more difficult to implement for a uniformity measurement. Therefore, if it can be confirmed that the center chromaticity gamut area using the RGBW test pattern sequence used in 5.4.1 yields the same value as the multicolor pattern, then the RGBW test pattern can be used for measuring chromaticity gamut area uniformity.

ADDITIONAL SETUP: The same setup conditions are used as the main section but using the RGBW test pattern (5.4.1) to determine the CIE 1931 chromaticity coordinates of the primary colors at maximum signal level at the standard virtual image positions defined in 19.5.

PROCEDURE: Same as main section.

ANALYSIS: See main section. Chromaticity gamut area nonuniformity is defined as:

$$N_{G_{Axy}} = 100\% \left[\frac{GA_{\max} - GA_{\min}}{GA_{\max}} \right] \quad (1)$$

where GA_{\max} and GA_{\min} are the maximum and minimum chromaticity gamut area values measured over the virtual image field.

REPORTING: Report all of the chromaticity gamut area values measured at the standard virtual image positions. See the example template for reporting the chromaticity gamut area nonuniformity below.

—SAMPLE DATA ONLY—								
Do not use any values shown to represent expected results of your measurements.								
CIE 1931 Chromaticity Gamut Area Uniformity Reporting Sheet (Darkroom Measurements)								
Device description: NED1, left eye								
Vantage-point method: Eye rotation			Test pattern: RGBW pattern (5.4.1)			Eye-point alignment method: Center by luminance		
Measurement position		Red		Green		Blue		CIE 1931 Chromaticity Gamut Area
9 pt.	5 pt.	x	y	x	y	x	y	GA_{xy}
1	1	0.5962	0.3603	0.3069	0.5948	0.1449	0.0878	27.6
2								
3	3	0.6217	0.3582	0.2979	0.6176	0.1436	0.1014	31.0
4								
5	5	0.6334	0.3532	0.3024	0.6009	0.1414	0.0839	31.6
6								
7	7	0.6195	0.3586	0.2951	0.6168	0.1438	0.1017	30.8
8								
9	9	0.6331	0.3458	0.3078	0.5961	0.1454	0.0868	30.9
Minimum								27.6
Maximum								31.6
CIE 1931 Chromaticity gamut area percent nonuniformity $N_{G_{Axy}}$								12.5



19.5.6 CHECKERBOARD CONTRAST RATIO WITH SMALL FOV LMD

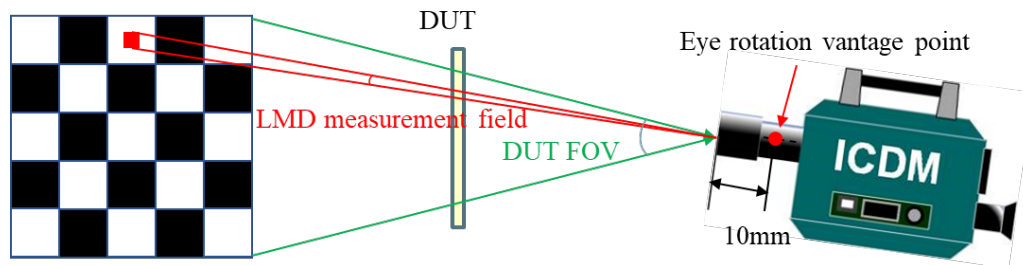
CAUTION: This measurement can be strongly affected by stray light for the black measurements. The LMD can be evaluated for its sensitivity to stray light. See CIE 244:2021. Characterization of imaging luminance measurement devices, Vienna, Austria, CIE 2021.

DESCRIPTION: Measure the black and white luminance at nine standard NED virtual image field points using the eye rotation vantage point method, then calculate the average contrast ratio. **Units:** none; and **Symbol:** C_{C-SFOV} .

The eye rotation vantage point method is used to pivot a relatively small field of view spot-type or 2D LMD (according to 19.2) to the standard measurement positions in the virtual image.

APPLICATION: This measurement can be used for any near eye display.

ADDITIONAL SETUP: The same as the main section, 19.5. The spot-type or 2D LMD (according to 19.2) has measurement field of 1° to 2° . The FOV of each box in the checkerboard needs to be at least 3 times the size of the measurement field of LMD to minimize the effect of stray light. The LMD measurement field should be centered within each of the white and black boxes of the checkerboard pattern near the standard five or nine positions of the virtual image (see 19.5, Fig. 1). The luminance measurements are then repeated at the same standard positions using an inverted checkerboard pattern. In order to simulate the impact of eye gaze, the eye rotation vantage point method is used to pivot the LMD to the appropriate measurement positions (see figure below). The figure indicates that the pivot point is 10 mm behind the LMD entrance pupil, assuming that the entrance pupil is at the front of the LMD. Alternatively, the LMD could be rotated about the entrance pupil position, but this would neglect any eye gaze motion.



PROCEDURE:

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis or eyeline.
2. Laterally position the LMD entrance pupil in the center of the eyebox, as specified by the manufacturer. If that position is not specified, use one of the eye point alignment methods in 19.3 to locate the eye-point and align the LMD to the center of the virtual image. Adjust the LMD for best focus at the center of the virtual image. This eye-point is the reference measurement location and is assumed to be roughly near the center of the NED eyebox.
3. Render the checkerboard pattern (with the center white box) shown above in the virtual image.
4. Use the eye rotation vantage point method to align the LMD to the center of the boxes at the standard virtual image positions defined in 19.5.
5. Measure the luminance values, L_{Wi} at the position P_i ($i = 1$ to 9) on the virtual image of the white center checkerboard pattern. Make sure the LMD measurement field is at the center of the box.
6. Invert the checkerboard pattern to obtain black boxes at the standard positions. Measure the luminance values, L_{Ki} at the position P_i ($i = 1$ to 9) on the virtual image of the black center checkerboard pattern. Make sure the LMD measurement field is at the center of the box.
7. Repeat for the other ocular, if applicable.

REPORTING: Report all of the luminance measurements, and contrast ratios, at the standard virtual image positions. Also report the average checkerboard contrast ratio, and the setup conditions.



19.5.7 CHECKERBOARD CONTRAST RATIO WITH LARGE FOV LMD

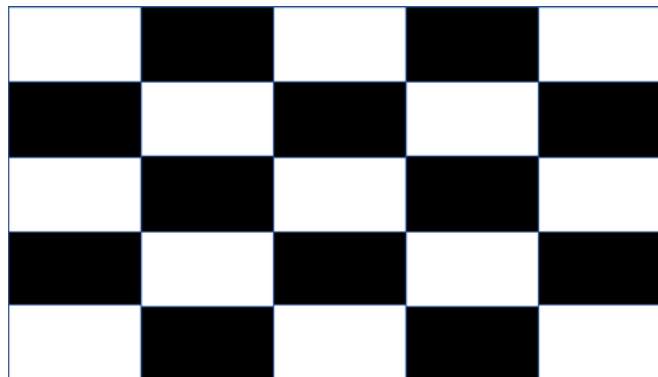
ALIAS: ANSI contrast

CAUTION: This measurement can be strongly affected by stray light for the black measurements. The LMD can be evaluated for its sensitivity to stray light. See CIE 244:2021. Characterization of imaging luminance measurement devices, Vienna, Austria, CIE 2021.

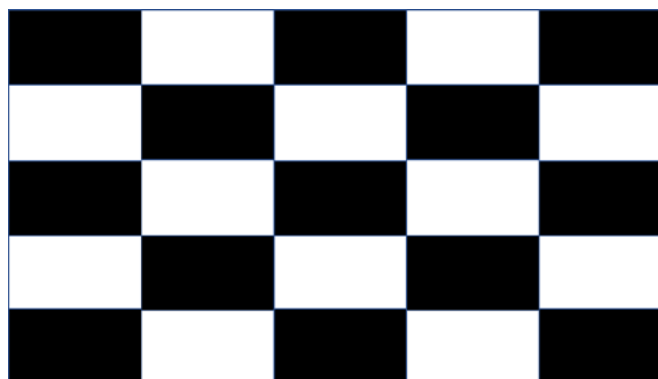
DESCRIPTION: Measure the black and white luminance at nine standard NED virtual image field points with the 2D LMD at a fixed entrance pupil position, then calculate the average contrast ratio. **Units:** none; and **Symbol:** C_{C-LFOV} .

The whole checkerboard pattern is captured in one image capture using a large FOV 2D LMD. This simulates the checkerboard contrast ratio for a fixed eye gaze and is equivalent to a spot-type LMD measurement using the pupil rotation vantage-point method. This method requires that the 2D LMD have a FOV larger than the virtual image of the NED. The camera should be calibrated to have a photopic response and corrected for spatial stray light. The 5x5 checkerboard patterns are used here as an example. Other checkerboard patterns, such as 4x4 checkerboard, could be used. The benefit of odd number checkerboard pattern such as 5x5 (shown below) is that the center contrast could be measured. The benefit of even number checkerboard pattern, such as 4x4, is that the number of black and white boxes are the same.

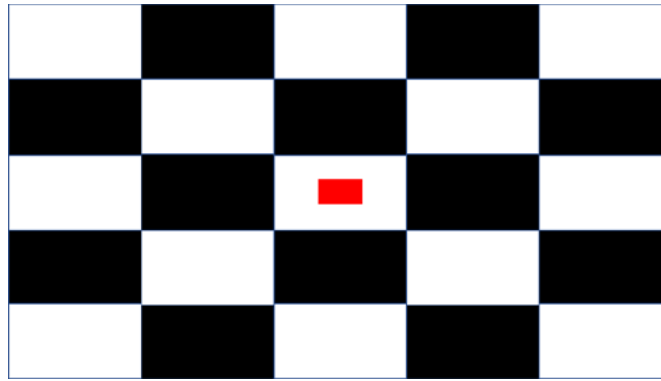
Image processing is used to determine the luminance at the center of the white and black boxes at the defined virtual image measurement positions. The measurement field or ROI of the LMD should be 1/3 the height and width of each box for determining the luminance. Five or nine measurement positions are recommended, approximately near the standard virtual image positions defined in 19.5, Fig. 1.



White center 5x5 checkerboard pattern



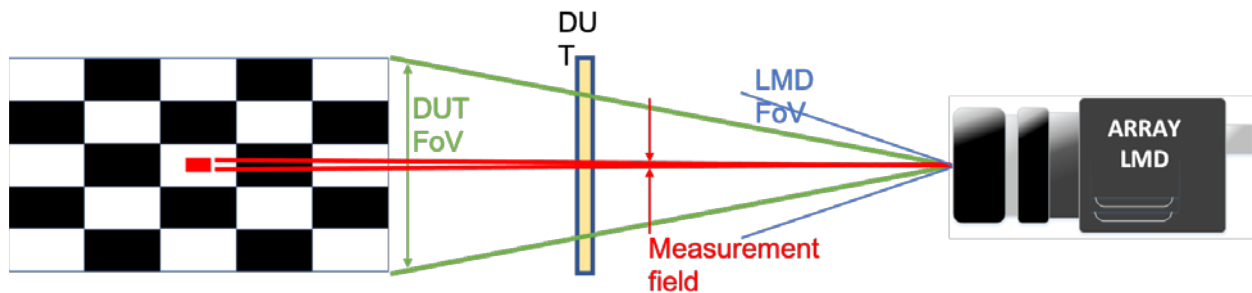
Black center 5x5 checkerboard pattern



Measurement area (red rectangle) for the white center box

APPLICATION: This measurement can be used for any near eye display but neglects the impact of eye rotation.

ADDITIONAL SETUP: To get the full FOV of the display, the LMD needs to have larger FOV than DUT.



PROCEDURE:

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis or eyeline.
2. Laterally position the LMD entrance pupil in the center of the eyebox, as specified by the manufacturer. If that position is not specified, use one of the eye point alignment methods in 19.3 to locate the eye-point and align the LMD to the center of the virtual image. Adjust the LMD for best focus at the center of the virtual image. This eye-point is the reference measurement location and is assumed to be roughly near the center of the NED eyebox.
3. Render the checkerboard pattern with the center white box in the virtual image.
4. Measure the luminance values, L_{Wi} at the position P_i ($i = 1, 3, 5, 7$, and 9) on the virtual image of the white center checkerboard pattern. The measurement horizontal and vertical field will be $1/3$ of the horizontal and vertical field of the box P_i .
5. Render the checkerboard pattern with the center black box in the virtual image.
6. Measure the luminance values, L_{Ki} at the position P_i ($i = 1, 3, 5, 7$, and 9) on the virtual image of the black center checkerboard pattern. The measurement horizontal and vertical field will be $1/3$ of the horizontal and vertical field of the box P_i , respectively. Repeat for the other ocular, if applicable.

ANALYSIS:

1. Calculate the contrast ratio $C_{C-LFOVi}$ at position P_i as follows:

$$C_{C-LFOVi} = \frac{L_{Wi}}{L_{Ki}}$$

2. The average contrast ratio ($C_{C-LFOVa}$) is calculated as follows:

$$C_{C-LFOVa} = \frac{1}{5} \sum_{i=1}^5 C_{C-LFOVi}$$

**REPORTING:**

1. The checkerboard patterns and corresponding FOV used in the measurement.
2. Luminance L_{wi} of white, luminance L_{Ki} of black and contrast ratio $C_c - L_{FOV_i}$ at each position P_i with the corresponding field angles at P_i ;
3. Average contrast $C_c - L_{FOV_a}$;
4. Eye relief (LMD position);
5. Type of LMD and aperture size.
6. Correction methods for measurement.

COMMENTS:

1. **Display Modes:** Like many metrics throughout this document, this measurement can be highly sensitive to the mode setting of the display.
2. **Report:** If a zero-luminance black is determined for the blacks, it is best to report an “undefined contrast” and include both the white luminance and the determined black luminance. In no case may the contrast be reported as infinite.



19.6 SPATIAL MEASUREMENTS

ALIAS: Michelson contrast, slant edge MTF, resolution

DESCRIPTION:

Measurements to determine the ability of the NED to show resolvable detail for vertical and horizontal grille patterns. The reference for this section will be what the eye is able to see as modeled by “A formula for the mean human optical modulation transfer function as a function of pupil size” (Watson, *Journal of Vision* 13(6):18, 1-11, 2013).¹ This section concentrates on how the eye would see a virtual image on a NED even though more detailed measurements may be desired that go beyond human visual acuity. These higher resolution measurements may be found in other or future sub sections.

Journal of Vision (2013) 13(6):18, 1-11

Watson

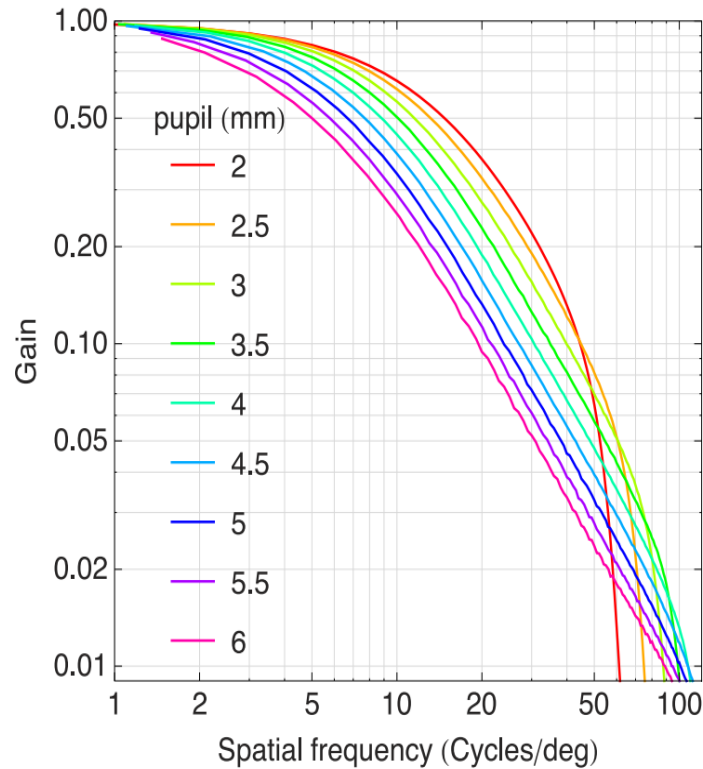


Fig. 1. Mean radial MTF for 2mm pupil diameter (Watson 2013) as a model of the human eye visual acuity limit.

¹ A. B. Watson, “A formula for the human optical modulation transfer function as a function of pupil size,” *Journal of Vision*, 13(6):1850, pp. 1-11, (2013).

19.7 NED LOCAL GEOMETRIC DISTORTION

ALIAS: geometric distortion, distortion

DESCRIPTION: This method uses a goniometer and camera to determine the amount of displacement of a rendered virtual image position to its idea position is measured for an array of positions over the entire virtual image. The method describes the measure of local geometric distortion when viewing through one eyepiece. **Units:** percent distortion. **Symbol:** D_{local} .

APPLICATION: This measurement can be used for any near eye display.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



OTHER SETUP CONDITIONS: This method is adapted from the camera distortion method described in ISO 17850¹. The method uses a camera mounted on a 5-axis goniometer or robot system to align the center of the entrance pupil at the eye point reference position, then perform an angular scan over the virtual image. Prior work demonstrated that the geometric distortion measured from a fixed camera measuring the full virtual image does not represent the distortion observed when the effect of eye gaze is included². Therefore, in order to include the influence of eye rotation on the geometric distortion, the pivot point used for angular scanning the virtual image field of view was 10 mm behind the entrance pupil of the camera. The center of the camera field of view was used to guide the goniometer to angular positions in the virtual image field of view. The distortion of the virtual image is sampled by a grid of uniformly spaced white dots rendered over the entire image. A fine dot spacing of no more than 2° is used to determine the ideal grid. A course dot spacing of spacing of no more than 10° is used to determine the geometric distortion over the entire virtual image. The fine and course grid pattern can be combined in one measurement, as illustrated in Fig. 1. A higher density of dots is preferred, depending on the need for finer measurement resolution. A grid of Red, Green, or Blue dots may also be rendered on a black background if it is useful to determine the geometric distortion of the individual primary colors.

Depending on the resolution of the NED, each white dot can be several display pixels in diameter, with clear separation between dots. The periodicity of the dot pattern should be designed such that a dot is located in the center of the virtual image. The camera should have at least 5 camera pixels in the orthogonal directions to accurately resolve the dot centroid. But the camera should have at least 20 camera pixels per degree. The centroid position (C_{xc}, C_{yc}) of each dot can be determined from the camera intensity map using the center of mass method:

$$C_{xc} = \frac{\sum x_{ci} I_i}{\sum I_i} \quad (1)$$

$$C_{yc} = \frac{\sum y_{ci} I_i}{\sum I_i} \quad (2)$$

where the position (x_c, y_c) of the i th camera pixel in the dot image has an intensity I_i . The camera intensity map should apply background sub-traction before the intensity values are used. Applying a 50% threshold requirement between the peak and signal floor values works well for well-behaved profiles. But a 2D median-filter smoothing may be necessary for noisy profiles. In addition, if the signal floor has significant slope, this sloped offset should be subtracted from the raw intensity data.

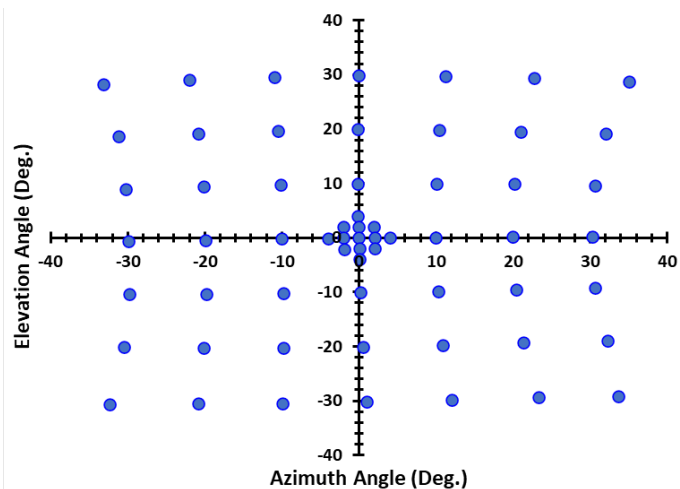


Fig. 1. Example of measured dot positions used for determining the local geometric distortion.

¹ ISO 17850:2015, “Ergonomics of human-system interaction – Part 392: Ergonomic recommendations for the reduction of visual fatigue from stereoscopic images,” International Organization for Standardization (2015).

² J. Penczek, M. Hasan, B. S. Denning, R. Capito, R. L. Austin, and P. A. Boynton, "Measuring interocular geometric distortion of near-eye displays," *SID Digest*, Vol. 50, pp. 430-433, (2019).



The goniometer pivots the camera to find the angular position of each dot when it is aligned to the center of the camera field of view. The angular accuracy of the goniometer will limit the accuracy of the distortion measurement. It is recommended to use a goniometer with $\leq 0.05^\circ$ angular accuracy.

PROCEDURE:

1. Align the center of the camera entrance pupil at the eye point of the NED device. The camera optical axis should be aligned with the center of the virtual image. Record what method was used to align the camera to the eye point.
2. Render a fine grid of uniformly spaced of white dots over the entire virtual image. There should be a dot at the center of the virtual image. Alternatively, combine the fine and course dot pattern as suggested in Fig. 1.
3. Use the goniometer to find the elevation and azimuth angles where the centroid of the center dot corresponds to the center of the camera field of view. Record the center dot position.
4. Repeat the goniometer eye rotation angular scan to find the elevation and azimuth angles of all the dots rendered over the virtual image. Record the angular positions of all the dots. The measured angular dot data may look similar to the example in Fig. 1.
5. If not already measured, render a course dot pattern and measure the centroid positions of each dot.

ANALYSIS: To determine the geometric distortion exhibited by the NED, it is necessary to compare the rendered virtual image dot positions to those of an ideal undistorted virtual image. Since the undistorted dot positions are not known, they must be inferred from the measured dot positions. The measured centroid dot positions from the fine grid pattern are used to determine the ideal undistorted dot positions extrapolated to large angles. It is assumed that the nearest neighbor dots to the center dot will have minimal geometric distortion. However, the ideal grid of dots, and the geometric distortion from those ideal dot positions must be determined in the projected plane of the virtual image, not in spherical coordinates.

A gnomonic equatorial projection (see Fig. 2) is needed to transform the elevation (θ) and azimuth (ϕ) angular coordinates for all the dots positions to locations on a virtual plane. Therefore, the spherical coordinates (ϕ, θ) of each dot position can be transformed to their cartesian coordinates (x', y') on a virtual plane by the following equations:

$$x' = \tan(\phi) \quad (3)$$

and

$$y' = \tan(\theta)/\cos(\phi) \quad (4)$$

An example of the measured course dot positions projected on the virtual plane is illustrated in Fig. 3 by the green circles. The ideal grid is derived by using only the fine grid measured dot positions projected on the virtual plane. The nearest neighbors from the center dot position are used to determine the horizontal periodicity $\Delta x'_{\text{fine}}$, vertical periodicity $\Delta y'_{\text{fine}}$, and rotation α of the ideal grid from the horizontal axis. The periodicity of the ideal course grid can be obtained by comparing the encoded distances (in pixels) between the fine and course dot centers in the original encoded test patterns. For example, if the test pattern for the fine grid had a horizontal period of $\Delta p_{x,\text{fine}}$ between dots, and the course test pattern had a period of $\Delta p_{x,\text{course}}$, then the horizontal period of the ideal course grid would be:

$$\Delta x'_{\text{course}} = \Delta x'_{\text{fine}} \frac{\Delta p_{x,\text{course}}}{\Delta p_{x,\text{fine}}} \quad (5)$$

A similar analysis would be used to find the vertical periodicity of the ideal course grid. Since it is not always possible to align the horizontal axis of the goniometer to the horizontal axis of the virtual image, the ideal grid may have a small rotation

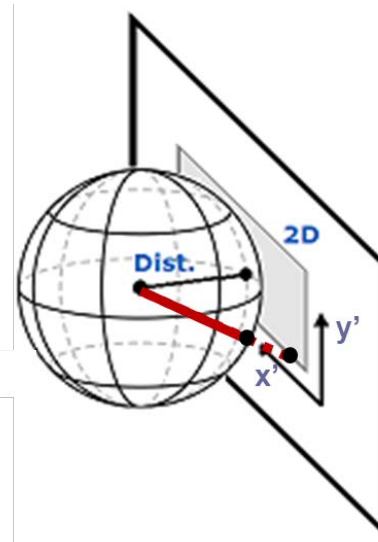


Fig. 2. Gnomonic equatorial projection from spherical coordinates onto a plane.

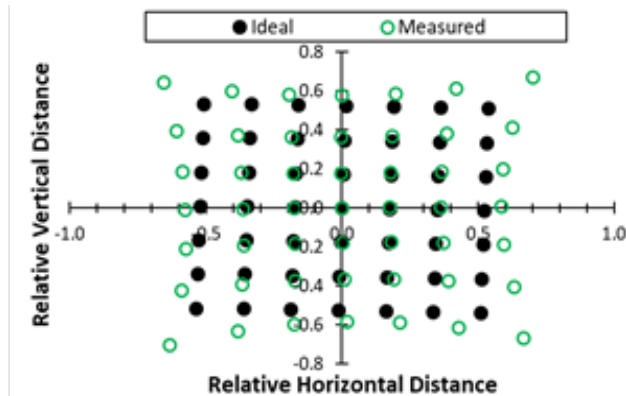


Fig. 3. Example of relative dot positions projected on a virtual plane.



α relative to the goniometer horizontal axis. In this case, the dot positions (x'_{ideal}, y'_{ideal}) of the ideal course grid would be given by:

$$x'_{ideal} = n \cdot \Delta x'_{course} \cdot \cos(\alpha) - m \cdot \Delta y'_{course} \cdot \sin(\alpha), \quad (6)$$

$$y'_{ideal} = n \cdot \Delta x'_{course} \cdot \sin(\alpha) + m \cdot \Delta y'_{course} \cdot \cos(\alpha) \quad (7)$$

where n and $m=0, \pm 1, \pm 2$, etc... indicate the horizontal and vertical, respectively, dot position indices in the ideal grid pattern. Once the full ideal grid of course dot positions is calculated, it can be compared with the measured dot grid (see darks circles in Fig. 3).

The sample data below provides an example of distortion measurements of fine (2°) and course (10°) dot position, and their derived idea grids.

—SAMPLE DATA ONLY—									
Do not use any values shown to represent expected results of your measurements.									
Fine dot grid (2 Deg dot grid)									
Measured dot angles Azimuth (ϕ)					Measured dot positions projected on plane x' position				
		-0.108					-0.00189		
	-2.058	-0.054	1.950			-0.0359	-0.00094	0.0340	
-4.003	-2.004	0.000	2.004	4.003	-0.0700	-0.0350	0	0.0350	0.0700
	-1.950	0.054	2.058			-0.0340	0.000945	0.0359	
		0.108					0.00189		
Elevation (θ)					y' position				
		4.00					0.0700		
	1.948	2.004	2.057			0.0340	0.0350	0.0359	
-0.108	-0.054	0.000	0.054	0.108	-0.0019	-0.0009	0.0000	0.0009	0.0019
	-2.057	-2.00	-1.95			-0.0359	-0.0350	-0.0340	
		-4.00					-0.0700		
					Ideal 2 Deg. dot grid				
					Horizontal x-axis dot period	Slope of horizontal line fit	Vertical y-axis dot period		
					0.035	0.027	0.035		



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Course dot grid (10 Deg dot grid)

Measured dot angles

Azimuth (ϕ)

-20.90	-10.50	-0.10	10.40	21.00
-20.20	-10.15	-0.10	10.05	20.15
-19.95	-10.00	0.00	10.00	20.00
-19.85	-9.80	0.20	10.25	20.40
-20.10	-9.80	0.50	10.90	21.40

Measured dot positions projected on plane

x' position

-0.382	-0.185	-0.002	0.184	0.384
-0.368	-0.179	-0.002	0.177	0.367
-0.363	-0.176	0.000	0.176	0.364
-0.361	-0.173	0.003	0.181	0.372
-0.366	-0.173	0.009	0.193	0.392

Elevation (θ)

19.20	19.60	19.90	19.80	19.50
9.50	9.80	9.90	9.95	9.85
-0.400	-0.200	0.00	0.100	0.200
-10.30	-10.20	-10.05	-9.80	-9.50
-20.30	-20.20	-20.05	-19.80	-19.30

y' position

0.373	0.362	0.362	0.366	0.379
0.178	0.175	0.175	0.178	0.185
-0.0074	-0.0035	0.0000	0.0018	0.0037
-0.193	-0.183	-0.177	-0.176	-0.179
-0.394	-0.373	-0.365	-0.367	-0.376

Ideal 10 Deg. dot grid generation

Horizontal x-axis dot period	Slope of horizontal line fit	Vertical y-axis dot period		$\Delta p_{\text{course}} / \Delta p_{\text{fine}}$
0.1742	0.027	0.1742		4.977

Ideal dot positions projected on plane

x' position

-0.358	-0.184	-0.009	0.165	0.339
-0.353	-0.179	-0.005	0.169	0.344
-0.348	-0.174	0.000	0.174	0.348
-0.344	-0.169	0.005	0.179	0.353
-0.339	-0.165	0.009	0.184	0.358

y' position

0.339	0.344	0.348	0.353	0.358
0.165	0.169	0.174	0.179	0.184
-0.0094	-0.0047	0.0000	0.0047	0.0094
-0.184	-0.179	-0.174	-0.169	-0.165
-0.358	-0.353	-0.348	-0.344	-0.339

Following the definition in ISO 17850, the local geometric distortion for a dot that is h' from the center relative to its corresponding idea distance from the center h is given by:

$$D_{\text{local}} = 100\% (h' - h)/h \quad (8)$$



REPORTING: Report the eye point alignment method, the dot color, size and periodicity, the angular scanning method, the raw angular dot positions, the ideal angular dot positions, and the percent distortion for each dot.

The percent local geometric distortion at each dot positions can then be reported in tabular form (see example below using example measured data above), or visualized by a false color contour map (as illustrated in Fig. 4). The distortion data may also be represented back in spherical/polar coordinates to illustrate how the distortion varies with gaze direction (see example in Fig. 5).

—SAMPLE DATA ONLY— Do not use any values shown to represent expected results of your measurements.					
ISO 17850 percent local distortion					
degree	-20	-10	0	10	20
20	8.3	4.4	3.9	5.1	9.5
10	5.0	1.8	0.2	2.0	5.5
0	4.2	1.2	0.0	1.2	4.5
-10	5.1	2.0	1.8	2.3	5.9
-20	9.1	5.6	4.8	6.3	10.2

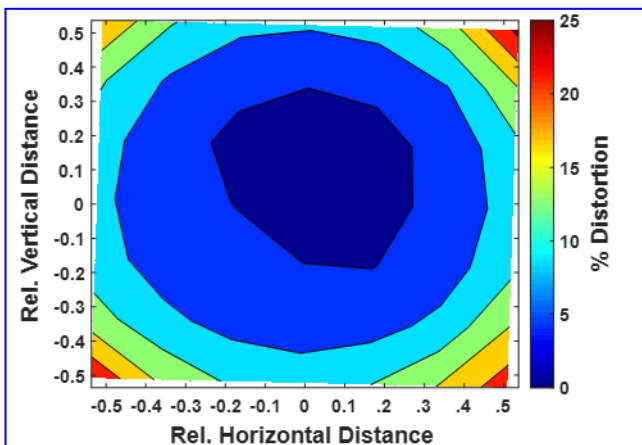


Figure 4. Example false color contour map of percent geometric distortion projected on the virtual plane.

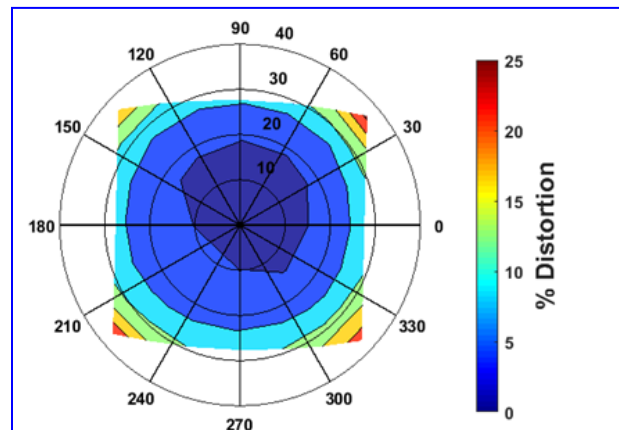


Figure 5. Example false color contour map of percent geometric distortion relative to gaze direction.

COMMENTS: None.



19.8 NED FIELD OF VIEW MEASUREMENTS

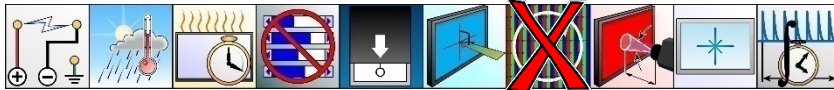
ALIAS: field of view (FOV) measurements

DESCRIPTION: Measure the field of view angular characteristics of a near eye display (NED) the way it is observed by a human user. That is by placing the entrance pupil (iris) at the center of the NED eyebox (eye point), then changing the viewing direction by rotating about the center of the eyeball, 10 mm behind the entrance pupil. This pivot point is called the eye rotation vantage-point (see 19.1 and 19.5) and serves as the reference viewing direction measurement method for NEDs. It is recommended that these field of view measurements match all vantage-point measurements using the eye rotation vantage-point method.

A pupil rotation vantage-point has also been used widely in industry. In this case, the measurements at various viewing directions are obtained by pivoting about the entrance pupil (see 19.1 and 19.5). This is typically employed when using a small entrance pupil with a wide field of view 2D LMD. Measurements taken by the pupil vantage-point method can sometimes correlate with the eye rotation vantage-point measurement results over narrow total field of view angles (<15 degrees). How much the pupil rotation measurements deviate from the eye rotation measurements will depend on the design characteristics of the NED, specifically the variation of results throughout the eye motion volume. Measurements taken with pupil rotation vantage-point geometry can only be presumed to correlate to the central 15 degrees. For larger viewing angles, it is possible to correlate the pupil rotation measurements from a particular NED device design to the reference eye rotation vantage-point measurements. An example is given in section 19.7 Virtual Image Geometric Distortion.¹ The general vantage-point method described in Section 19.5 is used to align the LMD to viewing directions in the virtual image. This is the reference starting point for the measurement of FOV, based either on luminance or Michelson contrast. The following procedure describes the process for measuring field of view of a NED where the display producing the virtual image is assumed to be rectangular.

APPLICATION: This measurement can be used for any near-eye display. It has been shown to give reproducible and repeatable measurement results for a broad range of NED design technologies. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2 and 19).



SETUP CONDITIONS FOR FIELD OF VIEW MEASUREMENT

A spot type LMD or 2D LMD according to 19.2 shall be used to measure the important characteristics of the NED virtual image. All evaluations are performed within a measurement field angle of ± 1 degree around the optical axis of the LMD. If another measurement field angle is used it shall be reported.

- The LMD needs to be aligned to the eye-point of the desired eyepiece. (See section 19.3)
- A goniometric motion apparatus is needed to scan over a range of viewing directions using the reference eye rotation vantage point method.
- The eye rotation vantage point method (19.3) can be implemented by holding the NED in a fixed position and mounting the LMD on a precision positioning system or other device which allows for pivoting in azimuth and elevation about the center of the eye. This allows for measurements of the desired positions in the virtual image field of the NED. Alternatively, the LMD can remain fixed, and the NED can be precisely positioned by pivoting about the same eye rotation vantage point.
- The eye-point position should be specified by the NED manufacturer. However, this is often not defined. If the eye relief is not specified, it will be assumed to be 25 mm along the NED optical axis (from the center of the last NED optic to the vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- The twenty five or nine positions illustrated in Fig. 1 are recommended.
- Measurement field angle (aperture): 2 degrees.
- The center luminance of the virtual image is measured and provides the reference value to calculate the edge threshold value.
- A full-screen test pattern of white color is used for relative luminance and resolution measurements.

¹ J. Penczek, M. Hasan, B. S. Denning, R. Capito, R. L. Austin, and P. A. Boynton, "Measuring interocular geometric distortion of near-eye displays," SID Digest, Vol. 50, pp. 430-433, (2019).

**PROCEDURE:**

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis or eyeline.
2. Laterally position the LMD entrance pupil in the center of the eyebox, as specified by the manufacturer. If that position is not specified, use one of the eye point alignment methods in 19.3 to locate the eye-point and align the LMD to the center of the virtual image. Adjust the LMD for best focus at the center of the virtual image.
3. Render an alignment target (such as in Fig. 1 with 9 or 25 cross hair locations) as the virtual image to identify the test point locations to be measured. The eye rotation vantage-point method is used to align the LMD (or NED device) to the appropriate measurement locations in the virtual image. The LMD alignment of each virtual image location can be recorded for future measurements, or the alignment pattern can be presented for aligning the LMD prior to each measurement. The nine virtual image positions illustrated in Fig. 1 are recommended, assuming the virtual image is rectangular. The center of the virtual image shall be measured in all cases.
4. Readjust the LMD focus as needed at each virtual image position in the visual field.
5. From the 9 or 25 starting measurement points, the edge of the FOV will be determined by first verifying that the FOV edge criteria is met at the reference point. If the criteria are met, then incrementally adjust the pointing direction. After each incremental change in the pointing direction, either the luminance or the contrast will be read and compared to the value specified for the definition of the edge. For the corner points, both elevation and azimuth pointing directions will be changed one at a time, returning to the reference test point before changing to the orthogonal pointing direction motion. If the edge criteria are not met at the test point, the angular test point is outside the FOV. In that case, the LMD shall be incrementally scanned toward the center until the threshold value is found.
6. For the 25-point test at the reference test points between the corners, only one pointing direction will need to be changed. Only the elevation along the top and bottom edges and only azimuth for the right and left edge test points need to be changed to find the incremental FOV location.
7. To determine the angular FOV extents, the total angular range shall be calculated as the total between two extreme edge measured locations nearest the test locations that roughly lie on a line through the center point. For the 9 point pattern of locations shown in Fig. 1, these distances would be between 1 and 9 (upper left, U.L. and lower right, L.R. points), 2 and 8 (upper center, U.C. and lower center, L.C. points), 3 and 7 (upper right, U.R. and lower left, L.L. points), 4 and 6 (left, L. and right, R. points). For the 25-point location pattern the following pairs of measured location shall be used 1 and 25, 2 and 24, 3 and 23, 4 and 22, 5 and 21, 6 and 20, 10 and 16, 11 and 15.
8. An example of the measurements of the field of view based on luminance for the 9-point pattern is given in the table below. The horizontal FOV is calculated from the maximum and minimum azimuth angle measurement points where the edge criteria are met. In the example case, 50% luminance value relative to the center luminance. In a similar way, the vertical FOV is calculated from the maximum and minimum elevation angle measurement points where the edge criteria are met. Equation (1) is used to calculate the angular range between the left and right or top and bottom edge criteria points based on the angular coordinate values of the edge criteria locations.

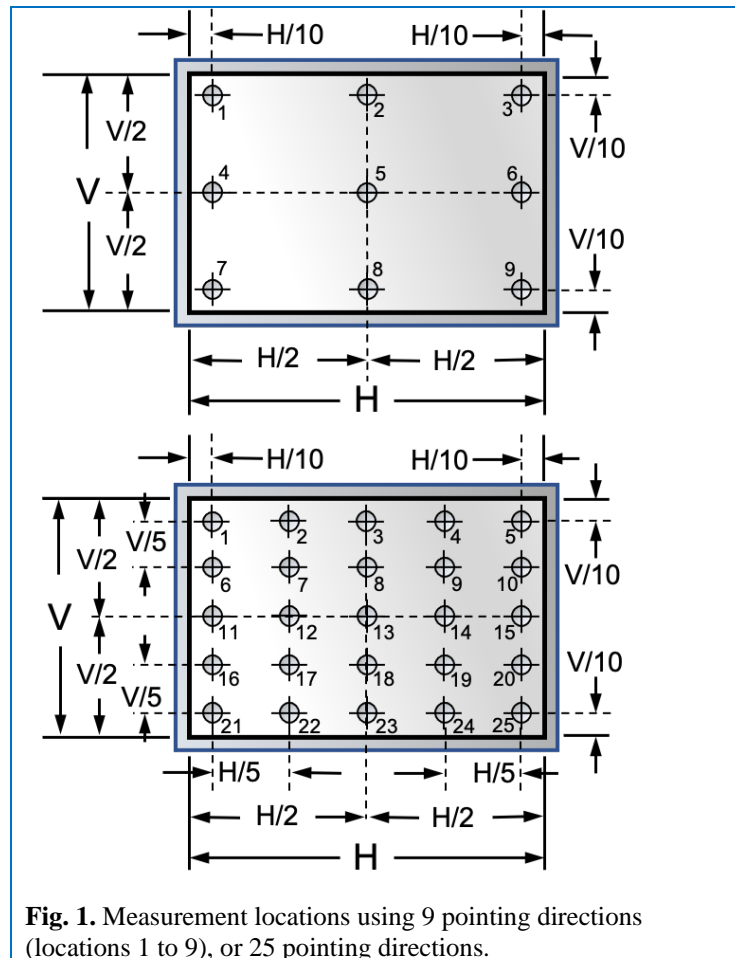


Fig. 1. Measurement locations using 9 pointing directions (locations 1 to 9), or 25 pointing directions.



—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Device description: NED1, left eye					
Reference points	Reference Point Elevation (θ) - degrees	Reference Point Azimuth (ϕ) - degrees	Luminance % relative to center at reference points	FOV edge Elevation (θ) - degrees	FOV edge Azimuth (ϕ) - degrees
Point 1, upper left, U.L.	8.1	-14.4	59	8.8	-15.6
Point 2, upper, U.C.	8.1	0	62	8.9	0
Point 3, upper right, U.R.	8.1	14.4	58	8.5	15.1
Point 4, left, L.	0	-14.4	66	0	-17.9
Point 5, center	0	0	100	0	0
Point 6, right, R.	0	14.4	64	0	17.8
Point 7, lower left, L.L.	-8.1	-14.4	58	-8.4	14.9
Point 8, center lower, L.C.	-8.1	0	61	-9.1	0
Point 9, lower right, L.R.	-8.1	14.4	58	-8.6	15.3
Reporting Example					
Horizontal and vertical FOV	Minimum	Max	Total		
Maximum horizontal Fov (from points 4 and 6)	-17.9	17.8	35.7		
Maximum vertical Fov (from points 2 and 8)	-9.1	8.9	18		
Diagonal FOV	Diagonal location	Diagonal location	Total		
Maximum extent between locations 1, 9	(-15.6,8.8)	(15.3,-8.6)	35.5		
Maximum extent between locations 3, 7	(15.1,8.5)	(14.9,-8.4)	34.4		
		Total Average	35		

ANALYSIS:

The field of view is calculated from the angular edge locations that are determined by the measurements of the specific edge criteria for either luminance or Michelson contrast. The locations are pairs of angular pointing direction for azimuth (ϕ) and elevation (θ), or (θ, ϕ). The field of view angular extents, D_{FOV} are calculated by adding together the left side of center distance $L(\theta, \phi)$, to the right side of center distance for $R(\theta, \phi)$ for the pairs of edge locations that lie on a line passing approximately through the center according to the following equation. For edge criteria points on the vertical axis upper center, $UC(\theta, \phi)$, to the lower center, $LC(\theta, \phi)$, the same equation can be used substituting $UC(\theta, \phi)$ for $L(\theta, \phi)$, and $LC(\theta, \phi)$, for $R(\theta, \phi)$.

$$D_{FOV} = \sqrt{(|L(\theta)| + |R(\theta)|)^2 + (|L(\phi)| + |R(\phi)|)^2} \quad (1)$$

REPORTING: From the measured results calculate the performance per the tables in the following sub-sections.

COMMENTS:

- Measurement distance:** If a less than or equal to 28 mm measurement distance is not achievable for a NED LMD due to size of the aperture mounting or lens, then it is not possible to use that particular NED LMD for this measurement.
- LMD mount geometrical center:** The mounting mechanism for the LMD must assure that the pivoting of the entrance pupil is at one of two allowed positions. The preferred choice for the pivot point is 10 mm behind the entrance pupil and along the optical axis of the detector (Eye Rotation vantage point). The other is in the plane of the entrance pupil of the LMD (pupil rotation vantage point). The selected vantage point must be reported since the measurement results will be different for the two vantage points.



19.8.1 FIELD OF VIEW BASED ON LUMINANCE

DESCRIPTION: Measure the center luminance as the reference for determining the edge of the field of view. **Units:** degrees and Candela/m²; and **Symbol:** various.

The NED FOV is determined by the boundary where the luminance of the virtual image drops below a specified value relative to the center luminance. Typical percentages used are 25% and 50%. The percentage is agreed upon by all interested parties. Unless stated otherwise, the luminance of white will be measured by supplying the display with the maximum signal for the R, G and B input channels.

ADDITIONAL SETUP: The same setup conditions are used as the main section.

PROCEDURE: Same as main section.

ANALYSIS: Same as main section.

REPORTING: Report values of all field of view edge points. See example template below.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Reporting example: Device description: NED1, left eye					
Parameter	Measured	Specification	Accept	Reject	Notes
FOV by Luminance	Cd/m ²	≥50% center			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
Pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	2-degree	2-degree			
Eye-point alignment	Section 19.3.1				
Reporting Example					
Horizontal pixels (N_H)	3200				
Vertical pixels (N_V)	1800				
Image width (H - Angle of the active area)	32	degrees			
Image height (V - Angle of the active area)	18	degrees			
Diagonal angle in degrees (D)	40.25	degrees			
Aspect Ratio	16:9				
Reference points	Reference Point Elevation (θ) - degrees	Reference Point Azimuth (ϕ) - degrees	Luminance % relative to center at reference points	FOV edge Elevation (θ) - degrees	FOV edge Azimuth (ϕ) - degrees
Point 1, upper left, U.L.	8.1	-14.4	59	8.8	-15.6
Point 2, center upper, U.C.	8.1	0	62	8.9	0
Point 3, upper right, U.R.	8.1	14.4	58	8.5	15.1
Point 4, left, L.	0	-14.4	66	0	-17.9
Point 5, center	0	0	100	0	0
Point 6, right, R.	0	14.4	64	0	17.8
Point 7, lower left, L.L.	-8.1	-14.4	58	-8.4	14.9
Point 8, lower center, L.C.	-8.1	0	61	-9.1	0
Point 9, lower right, L.R.	-8.1	14.4	58	-8.6	15.3
Reporting Example					
Horizontal and vertical FOV	Minimum	Max	Total		
Maximum horizontal FOV (from points 4 and 6)	-17.9	17.8	35.7		
Maximum vertical FOV (from points 2 and 8)	-9.1	8.9	18		
Diagonal FOV	Diagonal location	Diagonal location	Total		
Maximum extent between locations 1, 9	(-15.6,8.8)	(15.3,-8.6)	35.5		
Maximum extent between locations 3, 7	(15.1,8.5)	(14.9,-8.4)	34.4		
		Total Average	35		



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Reporting example: Device description: NED1, left eye

Parameter	Measured	Specification	Accept	Reject	Notes
FOV by Luminance	Cd/m ²	≥50% center luminance			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
Pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	2-degree	2-degree			
Eye-point alignment	Section 19.3.1				
Reporting Example					
Horizontal pixels (N_H)	3200				
Vertical pixels (N_V)	1800				
Image width (H - Angle of the active area)	32	degrees	+/-16		
Image height (V - Angle of the active area)	18	degrees	+/-9		
Diagonal angle in degrees (D)	40.25	degrees			
Aspect Ratio	16:9				
	Reference Point Elevation (θ) - degrees	Reference Point Azimuth (ϕ) - degrees	Luminance % relative to center at reference points	50% luminance FOV edge Elevation (θ) - degrees	50% luminance FOV edge Azimuth (ϕ) - degrees
Point 1	8.1	-14.4	59	8.8	-15.6
Point 2	8.1	-7.2	52	8.9	N/A
Point 3	8.1	0	54	9	N/A
Point 4	8.1	7.2	53	8.9	N/A
Point 5	8.1	14.4	58	8.5	15.1
Point 6	4.1	-14.4	52	N/A	-15.6
Point 7	4.1	-7.2	71	N/A	N/A
Point 8	4.1	0	89	N/A	N/A
Point 9	4.1	7.2	74	N/A	N/A
Point 10	4.1	14.4	68	N/A	16
Point 11	0	-14.4	66	N/A	-17.9
Point 12	0	-7.2	83	N/A	N/A
Point 13	0	0	100	N/A	N/A
Point 14	0	7.2	85	N/A	N/A
Point 15	0	14.4	64	0	17.8
Point 16	-4.1	-14.4	65	N/A	-17.4
Point 17	-4.1	-7.2	79	N/A	N/A
Point 18	-4.1	0	90	N/A	N/A
Point 19	-4.1	7.2	81	N/A	N/A
Point 20	-4.1	14.4	68	N/A	16.4
Point 21	-8.1	-14.4	58	-8.4	-14.9
Point 22	-8.1	-7.2	60	-8.7	N/A
Point 23	-8.1	0	61	-9.1	N/A
Point 24	-8.1	7.2	60	-8.8	N/A
Point 25	8.1	14.4	58	-8.6	15.3
Reporting Example					
Horizontal and vertical FOV	Minimum	Max	Total		
Maximum horizontal Fov (from points 3 and 23)	-17.9	17.8	35.7		
Maximum vertical Fov (from points 11 and 15)	-9.1	8.9	18		
Reporting Example (table continued)					



Diagonal FOV	Diagonal location	Diagonal location	Total		
Maximum extent between locations 1, 25	(-15.6,8.8)	(15.3,-8.6)	35.5		
Maximum extent between locations 5, 21	(15.1,8.5)	(14.9,-8.4)	34.4		
		Total Average	35		

NEAR EYE DISPLAYS

NEAR EYE DISPLAYS



19.8.2 FIELD OF VIEW BASED ON MICHELSON CONTRAST

DESCRIPTION: Measure the field of view as a function of the NED virtual image Michelson contrast. **Units:** degrees, cycles per degree, luminance; and **Symbol:** N/A

Michelson contrast measurements use a full-screen white grille test pattern. Unless stated otherwise, the luminance of white and the primary colors will be measured by supplying the display with the maximum signal for the R, G and B input channels (similar to 5.3 and 5.14). Both vertical and horizontal grille patterns will be required. The NED FOV is determined by the boundary where the Michelson contrast of the virtual image drops below a specified value.

ADDITIONAL SETUP: A 2D LMD must be used for these measurements with the method in Section 7.2 applied to the virtual image. Otherwise, the same setup conditions are used as the main section.

PROCEDURE: Same as main section.

ANALYSIS: The Michelson contrast at different pointing directions.

REPORTING: Report Michelson contrast and the maximum and minimum azimuth and elevation angles that meet the minimum Michelson contrast criteria for both vertical and horizontal grille patterns. Compute the total horizontal and vertical ranges. See example templates for vertical grille Michelson contrast reporting below.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Reporting example: Device description: NED1, left eye					
Parameter	Measured	Specification	Accept/Reject		Notes
FOV by Michelson contrast	Angles in degrees based on Michelson contrast ratio (Section 7.2)	$\geq 50\%$ Michelson contrast			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
LMD Entrance pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	- degree	2-degree			
Eye-point alignment	Section 19.3.1				
LMD resolution	254 pixels/degree	240 pixel/degree			
Reporting Example					
Horizontal pixels (N_H)	3200				
Vertical pixels (N_V)	1800				
Image width (H - Angle of the active area)	53.3	degrees	+/-26.66		
Image height (V - Angle of the active area)	30	degrees	+/-15		
Diagonal angle in degrees (D)	61.2	degrees			
Aspect Ratio	16:9				
Grille pattern orientation	vertical	vertical or horizontal			
Grille pattern frequency	2 on 2 off	Max 1 on 1 off			
Grille pattern frequency	15	cycles/degree			
	Reference point Elevation (θ) - degrees	Reference point Azimuth (ϕ) - degrees	Measured Michelson contrast %	FOV edge Elevation (θ) - degrees	FOV edge Azimuth (ϕ) - degrees
Point 1	12	-23.3	50	15.3	-26.6
Point 2	12	-11.65	55	15.2	-11.65
Point 3	12	0	72	15.2	0
Point 4	12	11.65	58	15.1	11.65
Point 5	12	23.3	51	15	26.4
Point 6	6	-23.3	56	6	-26.4
Point 7	6	-11.65	61	N/A	N/A



Point 8	6	0	76	N/A	N/A
Point 9	6	11.65	63	N/A	N/A
Point 10	6	23.3	53	6	26.3
Point 11	0	-23.3	58	N/A	-26.3
Point 12	0	-11.65	75	N/A	N/A
Point 13	0	0	80	N/A	N/A
Point 14	0	11.65	74	N/A	N/A
Point 15	0	23.3	60	N/A	27.2
Point 16	-6	-23.3	57	-6	-26.2
Point 17	-6	-11.65	64	N/A	N/A
Point 18	-6	0	77	N/A	N/A
Point 19	-6	11.65	63	N/A	N/A
Point 20	-6	23.3	59	-6	26.5
Point 21	-12	-23.3	55	-14.4	-26
Point 22	-12	-11.65	61	-14.9	-11.65
Point 23	-12	0	69	-14.9	0
Point 24	-12	11.65	62	-14.7	11.65
Point 25	-12	23.3	50	-12.5	23.3
Reporting Example					
Horizontal and vertical FOV	Minimum	Max	Total		
Maximum extent between locations 11 to 15	-26.3	27.2	53.5		
Maximum extent between locations 3 to 23	-14.9	15.2	30.1		
Diagonal FOV	Diagonal location	Diagonal location	Total		
Maximum extent between locations 1 to 25	(-26.6, 15.3)	(23.3, -12.5)	57.1		
Maximum extent between locations 5 to 21	(26.4, 15)	(-26, -14.4)	60.1		
			Total Average		
Average diagonal FOV ((Total 1 to 25) + (Total 5 to 21))/2			58.6		



19.9 EYEBOX

ALIAS: Eyebox Measurements, Eyebox Dimensions, Qualified Viewing Space, QVS

DESCRIPTION: Measure the three-dimensional eyebox about the reference eye-point of the NED.

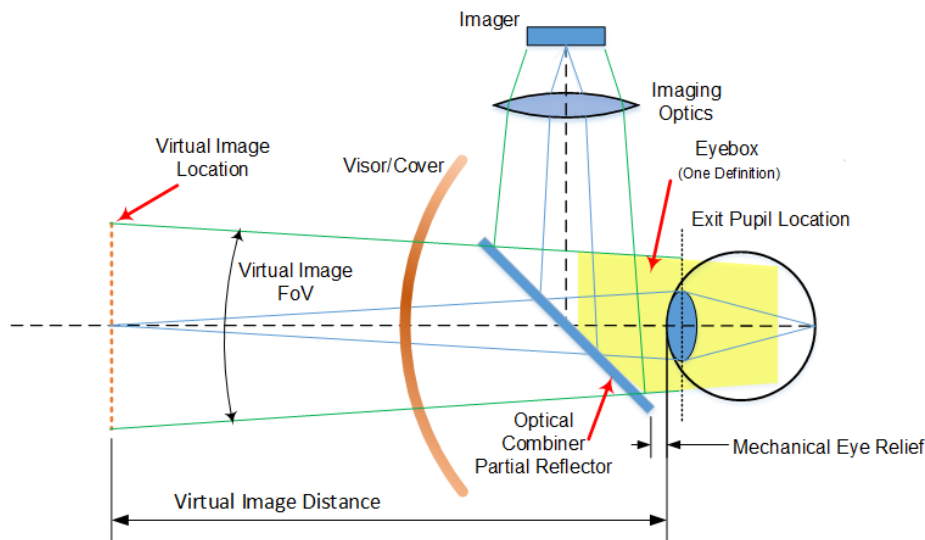


Fig. 1. Basic AR-type NED Virtual Image and Eyebox

The eyebox is a critical parameter of the AR/VR optical system and the dimensions of the eyebox determine many of the performance characteristics of the near eye display (NED). Unfortunately, there exist many variants of the definition of the eyebox, and these have led to complications in the measurement of the eyebox¹. The size and shape of the eyebox are dependent on many optical system parameters such that the eyebox varies depending on the method for the generation of the computer generated virtual image and method for combining the virtual image with the real-world view (ambient scene) for augmented reality NEDs². Figure 1 illustrates a simple

augmented reality (AR) NED showing the virtual image and the eyebox, by one definition.

From the optical design perspective, the definition of the eyebox begins with the image-forming optical system exit pupil. The exit pupil is the image, in image space, of the optical system aperture stop³. The aperture stop may be a physical aperture located at a specific spot in the optical system or, it may default to the clear aperture of one of the optical elements such as a lens or, a mirror, that becomes the limiting aperture for light rays transmitted by the optical system into image space. The aperture stop may be circular in shape (if it is formed by a lens element) or, rectangular (if it formed by a rectangular fold mirror, for example). For many NED devices, it is beneficial for the aperture stop (and, hence, the exit pupil) to be rectangular as the virtual image generally is rectangular and the rectangular aperture may reduce stray light or, reflections from entering the user's field of view (FOV). It is generally preferable for the exit pupil to be larger than the nominal eye pupil dimension to allow for some gaze motion of the user's eye without losing part of the image. The center point of the exit pupil is the eye-point⁴ as described in section 19.1.

The position of the exit pupil is defined primarily by the desired eye relief of the near-eye optical system. From the introduction, eye relief is defined as the distance along the optical axis (or, eyeline) from the last optical element of the DUT to the vertex of the cornea. Eye relief is the specification most frequently used by NED manufacturers since it describes the physical distance from the NED optics to the user's eye. Similarly, the distance along the optical axis from the nearest optical element to the location of the eye pupil is the pupillary distance (PD). For mechanical purposes, the "mechanical" eye relief is considered to be the distance from last point on the last optical element to the first part of the user's face that could contact the last optical element. This could include prescription eyewear, eyelashes or, any structure around the eye such as facial bone structure. In Fig. 1, this would be the distance from the lower right edge of the partial mirror beam combiner to the eye cornea. The eye relief distance may range from about 16 mm for spectacle eyewear (and some microscopes) to 28 mm, to allow the user to wear personal eyeglasses. In the case of rifle scopes, the eye relief distance, for mechanical purposes, more typically is about 5 inches to allow for weapon recoil⁵.

Depending on the imaging optical system design the exit pupil location may not be useful for determining eye relief. The exit pupil may be located at infinity if the optical system is telecentric in image space. This is common in laser-based optical systems and may produce a very small exit pupil diameter. Scanning laser near-eye displays may be an example and may require some form of pupil expansion or, pupil replication to provide a sufficiently large exit pupil for comfortable human viewing. Also, some optical systems may produce a virtual exit pupil when viewed from image space. Indeed some simple eyepiece designs implementing a negative lens as the last element produce a virtual exit pupil. In this case, eye relief only can be defined mechanically.

While the cross-section size and shape of the eyebox (exit pupil) are straightforward, the depth of the eyebox is the source of much discussion and variations in definition. Generally, the eyebox volume is considered to extend from the nearest optical surface point to slightly beyond the exit pupil location as shown in Fig. 1. The definition of eyebox from the chapter 19 introduction states that it is the volume around the eye-point that allows observation of the entire virtual image FOV



without degradation. Generally, degradation results in the reduction of the field of view due to vignetting. However, degradation also may be defined by a reduction of luminance, Michelson contrast, increasing distortion or, increasing lateral chromatic aberration. Measurement results are dependent on the pupil size of the LMD and the measurement parameter (e.g., luminance, color, or Michelson contrast) used to determine the FOV boundary⁶. This assumes that the exit pupil is sufficiently larger than the eye pupil to allow for eye-center rotation without loss of FOV – not always true for near-eye optical systems. More generally, the eyebox is defined for most visual instruments (such as microscopes, telescopes, endoscopes, binoculars and, gun scopes) by the manufacturer as the volume that extends from the last optical surface through the exit pupil to the maximum eye relief location along the optical (z) axis, where the maximum eye relief distance is defined by the allowable degradation of the FOV. Generally, the cross-sectional dimension of the eyebox decreases beyond the exit pupil location. Thus, the eyebox cross-section dimension may be largest at the last optical element surface and smallest at the maximum eye relief location. This forms either a truncated cone (for circular aperture stops) or, a truncated pyramid (for rectangular aperture stops) shape to the volume of the eyebox that is often depicted in the literature¹. Depending on the imaging optical system design, the eyebox may take a very different shape – a diamond shape in 2D rendering or, in 3D, a biconical shape if the cross-section is circular or, octahedral if the cross-section is rectangular. Frequently, this occurs when the emission divergence or, spread from the display elements is narrow⁷ as illustrated in Fig. 2. The reduction in size with distance from the last optical surface also is the case in general for the exit pupil – the cross-section dimension of the exit pupil (in optical design) is inversely proportional to the eye relief distance and inversely proportional to the extent of the virtual image FOV. For many visual instruments, the eyebox depth is further restricted to be between the minimum and the maximum eye relief locations. This is the case for the aforementioned rifle scope and for most HUD systems since the greatly extended eye relief distance dictates that the eyebox depth will be limited by the depth of focus (dependent on the $f\#$) of the image forming optical system.

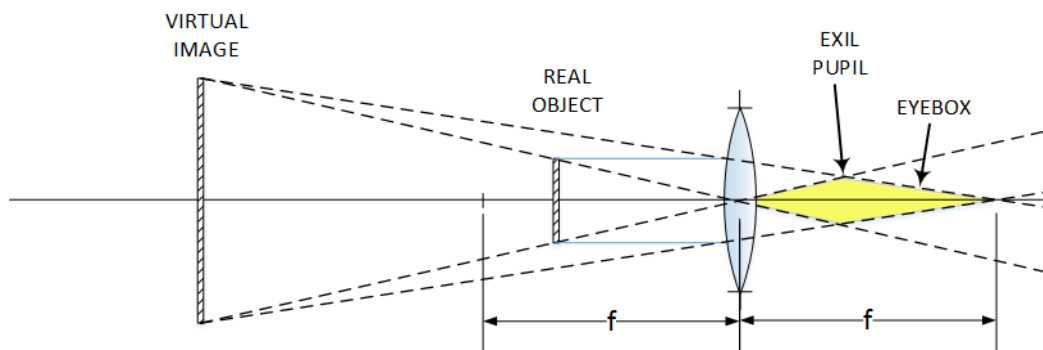


Fig. 2. Simplified, unfolded near-eye optical system showing virtual image, exit pupil and eyebox.

The many characteristics of the eyebox and their various limitations and dependencies noted above indicate that the design or specification of the eyebox presents one of the most difficult design problems for the NED device. For example, returning again to the example of the rifle scope: to extend the exit pupil distance to the required position requires that the image forming optical system is very complex and involves many optical elements – an impracticality for a wearable NED. The need for an exit pupil large enough to allow for full gaze movement about the eye center of rotation⁸ and for mechanical motion of the NED optics relative to the head or face of the user due to walking or head movements places additional design constraints on the eyebox⁹. Additionally, contemporary NED designs, especially AR-types are quite varied in design such that the descriptions above may not be fully applicable for all design configurations. (See section 19.10 for figures illustrating the most common configurations for optically-combined AR-type NED devices.) For example, laser-scanning based NEDs exhibit extremely small exit pupils, requiring some form of refractive, reflective, or diffractive pupil expansion or replication (see Fig 5 in section 19.10.) Waveguide[†] based NED devices typically exhibit very large eyebox cross-sections since the waveguide layout on the optical substrate forms the image source. As with other NEDs, the larger the eye relief needed, the smaller the exit pupil size. But, for eyewear-type devices where the eye relief may be relatively small, the exit pupil will be large and allow for large eye rotation movement. For head-up displays (HUDs) the eyebox (aka, the head-motion box) consists of a cylindrical volume of collimated rays of light that typically measures 5 inches lateral by 3 inches vertical with a

[†] Strictly, these are light guides, not waveguides since light propagates by total internal reflection (TIR) as long as the surface-incidence angle remains greater than the critical angle. No propagation modes form within the guide medium.



depth of about 6 inches, allowing the viewer some freedom of head movement without losing the image information¹⁰. However, movement too far away from the display source will cause the image to crop off around the edge due to vignetting.

Figure 2 illustrates a simplified optical system consisting of a single thin lens showing the relevant parameters of the virtual image, exit pupil and eyebox (by one definition). Here, the real object may be the display imager device such as a DLP, LCOS or, OLED or, the intermediate real image formed within the NED optical system. The figure also shows the relationship of the optics focal length and object and image distances. Note, however, that a single thin lens will not produce a very good virtual image. This simple configuration would be subject to various aberrations including axial and lateral color.

COMMENT: Some mechanical motion devices – both linear and angular – exhibit backlash, the offset in position due to mechanical gearing spacing. It is extremely important that backlash be eliminated or, accounted for in these measurements. Backlash is a systematic statistical bias and may contribute non-negligible measurement error. If unknown, perform backlash measurements on devices prior to display testing. If found, implement backlash mitigation methods as needed.

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- ⁶ Austin, R. L., Denning, B. S., Drews, B. C., Fedoriouk, V. B., et al, “Qualified viewing space determination of near-eye and head-up displays,” Journal of the Society for Information Display, vol. 26, issue 9, p. 567-575.
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- ⁹ Karl G, “Near Eye AR/VR and HUD Metrics For Resolution, FOV, Brightness, and Eyebbox/Pupil,” blog post, October 13, 2016.
- ¹⁰ Spitzer, C. R., “Digital Avionics Handbook”, CRC Press, p. 4, 2000, ISBN 978-1-4200-3687-9.



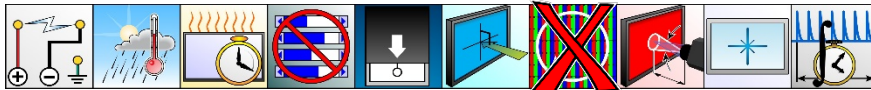
19.9.1 CENTER LUMINANCE METHOD

DESCRIPTION: This method determines the eyebox boundary by measuring the virtual image center luminance as the LMD entrance pupil is translated about the eye-point. The luminance threshold for determination of the eyebox dimensions generally is a percentage of the center luminance as measured with the center of the LMD entrance pupil located at the eye-point. Typically, the threshold is 25% or, 50%. The measured dimension of the eyebox will depend on the threshold percentage selected. For the procedure description that follows, a 50% threshold is used. However, it is important that the selected threshold percentage be agreed upon by all stakeholders and that the threshold percentage is clearly recorded in the test results. Also, note well that virtual image focal distance – the location of the virtual image in image space in front of the viewer – also may affect the determination of the eyebox dimensions. Depending on the design and application for the NED, the virtual image focal distance may be anywhere from approximately 15 inches to infinity. While the virtual image FOV may appear the same over this range, the eyebox measurements may vary – especially if the focal distance is less than about 1 meter. Maintaining the measurement location at the center of the virtual image while translating the LMD entrance pupil across the eyebox may require angular compensation – especially if the virtual image focal distance is small. The virtual image focal distance also shall be reported in the test results. Any angular compensation (θ , ϕ in degrees) needed also shall be reported in the test results.

APPLICATION: This measurement can be used for any NED or HUD. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

Caution: This method does not require that the entire field of view is above the required threshold value, only that the luminance at the center of the field of view remains above the luminance threshold. Therefore, this method generally overestimates the eyebox size than if the entire field of view is considered. Section 19.9.4 describes an alternative method that may produce more accurate results.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR EYEBOX MEASUREMENT – CENTER LUMINANCE METHOD

The alignment method can be used with a spot-type or 2D LMD (see 19.2).

- At least a 5-axis motion apparatus is needed to scan over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. The setup using a spot-type LMD and, as an example, an AR-type NED is shown in Fig. 1.
- Note: The procedure in this section is written for use with fully-manual mechanical motion devices. If a fully-automated system is available, consider using the procedure described in section 19.9.4.
- The eye rotation vantage point method (19.5) generally is used to scan over the virtual image field of view. In that case, the entrance pupil is placed at the eye-point (19.3) and the LMD is pivoted about a position 10 mm behind it (to simulate eye gaze). Alternatively, the pupil rotation vantage point method (19.5) also can be used to scan the virtual image FOV but, this method neglects the impact of eye gaze.
- The measurement distance between the NED and the LMD should be specified by the manufacturer. However, this is often not defined. If the eye relief is not specified, it shall be assumed to be 25 mm (from the center of the last NED optical element to the vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- For a spot-type LMD, the measurement field angle (aperture) is typically 2 degrees full angle. When using the spot-type LMD, it is valuable also to view the 2D virtual image around the measurement field angle.
- When using a 2D LMD, the LMD should have a photopic response, a 2 by 2 degree region of interest (measurement area), and it is useful to have a FOV that is larger than the virtual image. The 2D LMD should have background, flat field, and geometric corrections applied.
- The test pattern for this measurement is a full-field white pattern.

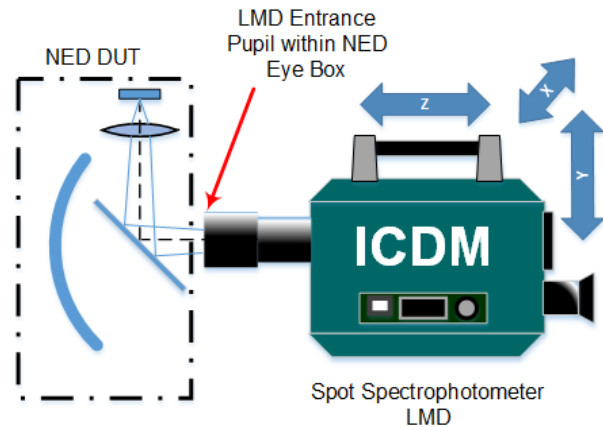


Fig. 1. Luminance Method Setup.



- A rough visual alignment of the LMD can be made by placing the LMD entrance pupil at the approximate center of the light field projected behind the NED or HUD, see Fig. 2.

PROCEDURE, EYEBOX CROSS-SECTION:

This procedure determines the cross-sectional eyebox at the reference eye-point based on the virtual image center luminance.

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the NED to be measured. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis (z-axis) or eyeline. Record the distance,
2. Laterally position the LMD entrance pupil approximately in the center of the light field projected behind the NED (see Fig. 2).
3. Render an alignment target (such as a crosshair) as the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
4. Use the eye rotation vantage point method (19.5) to rotate the LMD FOV to the center of the virtual image.
5. Present the full-field white test pattern for the eyebox measurement and measure and record the center luminance.
6. Translate the LMD in the -x direction while viewing and measuring the virtual image center luminance. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the negative x-axis position of the LMD where the virtual image luminance reaches a desired threshold value (for example, 50 % of the luminance measured at the eye-point). The virtual image pattern may begin to fade at one edge as illustrated in Fig. 3a) as the LMD is translated. As the center luminance measurement decreases to the desired threshold level, the virtual image may appear similar to that shown in Fig. 3b) and the edge of the exit pupil may be visible at the edge of the virtual image. Record the LMD distance traveled from the eye-point.
7. Translate the LMD in the + x direction while viewing and measuring the virtual image luminance. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the positive x-axis position of the LMD where the virtual image luminance reaches the same threshold value. Record the LMD distance traveled from the eyepoint.
8. Use the negative and positive x-axis boundary positions that produced the desired threshold value and calculate the x-axis dimension between those boundaries. Also calculate the approximate midpoint of the eyebox. Translate the LMD to that midpoint position and reset this as the new x=0 position.
9. Translate the LMD in the + y direction while viewing and measuring the virtual image center luminance. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the positive y-axis position of the LMD where the virtual image luminance reaches the same threshold value. Record the LMD distance traveled from the eyepoint.
10. Translate the LMD in the - y direction while viewing and measuring the virtual image luminance. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the negative y-axis position of the LMD where the virtual image luminance reaches the same threshold value. Record the LMD distance traveled from the eyepoint.
11. Use the negative and positive y-axis boundary positions that produced the desired threshold value and calculate the y-axis dimension between those boundaries. Also calculate the approximate vertical midpoint of the eyebox. Translate the LMD to that mid-point position and reset this as the new y=0 position.

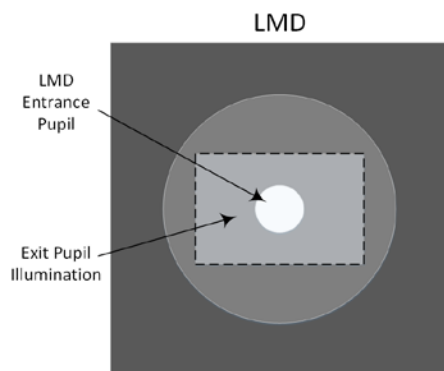


Fig. 2. Rough visual alignment of the eyebox and LMD



Fig. 3. a) Full-field Luminance as LMD approaches the edge of the eyebox; b) Luminance reduced to ~50% at center of field. Note: edge of exit pupil may be visible.



12. *Optional corner point measurement:* Repeat steps 6 through 11 to measure the x, y travel distances to the virtual image corners: upper left (UL), upper right (UR), lower left (LL) and, lower right (LR) and record LMD travel distances from the eye-point.
13. Use the UL and LR boundary positions that produced the desired threshold value and calculate the back diagonal dimension between those boundaries. Use the UR and LL boundary positions that produced the desired threshold value and calculate the forward diagonal dimension between those boundaries. Also calculate the approximate vertical and horizontal midpoint of the eyebox. Translate the LMD to that mid-point position and reset this as the new x=y=0 position.
14. Repeat steps 6 to 11 (6 to 13 if corner point measurement option is selected) until the x-axis and y-axis mid-points are within 1 mm from the previous x=y=0 position (the origin for the NED DUT).
15. Record the absolute coordinates of the final eyebox horizontal and vertical dimensions and the mean width and height of the eyebox for the NED DUT. Include the mean forward diagonal (FD) and back diagonal (BD) measurements if corner measurements option is selected, where FD is defined as UR + LL, and BD is defined as UL + LR.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

**Table 1. Eyebox Data Example:
Center Luminance Measurements with 50% Threshold**

Device Description				NED Device 1				Left Ocular					
Parameter				Measured		Specification		Accept		Reject		Notes	
Eyebox Dimensions by Luminance				Cd/m^2		≥ 50% center							
Eye relief (remember 3 mm Cornea offset)				25 mm		25 mm							
Pupil distance				28 mm		28 mm							
LMD Pupil diameter				5 mm		2-5 mm							
Measurement vantage point				Eye rotation		Eye rotation							
Measurement field angle				±1 degree		±1 degree							
Pointing direction alignment				Section 19.3.1									
Virtual Image Focal Distance				1 m		1 diopter							
	Center			Translate Left		Translate Right		Translate Up		Translate Down			
Measurement Location	L (cd/m²)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)		
Virtual Image Center	875.0	0.0	0.0	-4.2	0.0	4.15	0.0	0.0	3.45	0.0	-3.4		
Angular Compensation (if needed)				θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)		
Measured (degrees, °)				0.23	0.0	-0.24	0.0	0.0	-0.2	0.0	0.19		
Δx (mm)				4.2		4.15							
Δy (mm)									3.45		3.4		
Mean horizontal eyebox (mm)				8.35									
Mean vertical eyebox (mm)								6.85					
Optional Corner Measurements													
	Center			Translate Upper Right		Translate Lower Left		Translate Upper Left		Translate Lower Right			
Measurement Location	L (cd/m²)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)		
Virtual Image Center	875.0	0.0	0.0	3.65	3.25	-3.65	-3.2	-3.7	3.3	3.6	-3.25		
Angular Compensation (if needed)				θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	θ (°)	φ (°)	φ (°)		
Measured (degrees, °)				-0.21	-0.19	-0.21	-0.19	0.21	-0.19	-0.21	0.19		
Δx (mm)				3.65		3.65		3.7		3.6			
Δy (mm)					3.25		3.2		3.3		3.25		
Mean forward diagonal eyebox (mm)				9.74									
Mean back diagonal eyebox (mm)								9.81					

Note that the above procedure measures the height and width (or, diagonal) of the exit pupil or, the height and width (or, diagonal) of the eyebox at the location of the eye-point. The depth range of the eyebox also shall be determined. To accomplish this, first, the *eyeline* must be established. Generally, it may be assumed that the eyeline is coincident with the optical axis of the NED. However, this may not always be the case. To establish the eyeline, the LMD should be moved away



from the eye-point position along the z-axis for some distance. This distance may be a few millimeters. If the image of the full-field white pattern begins to deteriorate around the edges due to vignetting, then LMD has been moved too far. Slowly move the LMD back toward the eye-point until the edges of the full-field white pattern are just discernable, if, perhaps, a little fuzzy (i.e., slightly out of focus.) Repeat the above procedure, steps 6 through 11 and 14 or, follow the procedure in Section 19.3, to locate the eye-point. If the new determination of the axial pupil point location relative to the eye-point location remains at $x = y = 0.0$, then the eyeline coincides with the NED optical axis. If the new eye-point is located at $x \neq y \neq 0.0$, then the eyeline is not coincident with the optical axis of the NED. In this case, use the θ and ϕ goniometer adjustments for the NED to align the eyeline to the z-axis of the LMD.

PROCEDURE, EYEBOX VOLUME:

This procedure determines the three-dimensional eyebox about the reference eye-point based on the virtual image center luminance.

1. Move the LMD back to the position of the original eye-point.
2. Move the LMD in small steps, perhaps 1 mm, away from the original eye-point and NED along the eyeline and repeat the above eyebox cross-section procedure, steps 6 – 11, at each step position until reaching the point where the full-field white pattern edges begin to deteriorate.
3. Record the results for each step position in a table similar to Table 1, above.
4. Move the LMD back to the original eye-point location and then move the LMD closer to the NED along the eyeline in small steps of the same size used when moving the LMD away from the eye-point.
5. Repeat the eyebox cross-section procedure above, steps 6 – 11, for each step position and record the results in tables such as Table 1.
6. Continue this process until a reasonable inside distance has been reached, such as a minimum eye relief distance of 21 mm (+3 mm, corneal thickness.)
7. *Optional corner point measurement:* Repeat the above procedure steps 2 – 6 for the corner points: UL, UR, LL and, LR.
8. Use the results to record the mean eyebox height, width, forward and back diagonals as shown in Table 2.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Table 2. Data Example: Eyebox dimension along z-axis					
Device Description	NED Device 1		Left Ocular		
Parameter	Measured	Specification	Accept	Reject	Notes
Eyebox Dimensions by Luminance	Cd/m ²	≥ 50% center			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
LMD Pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	±1 degree	±1 degree			
Pointing direction alignment	Section 19.3.1				
Virtual Image Focal Distance	1 m	1 diopter			
Eyeline Position (relative to Eye-point)	Mean Horizontal Eyebox Dimension	Mean Vertical Eyebox Dimension	Mean Forward Diagonal Dimensions	Mean Back Diagonal Dimensions	Units
-4.0 mm	11.32	9.29	14.59	14.62	mm
-3.0 mm	10.61	8.70	13.65	13.71	mm
-2.0 mm	9.75	8.00	12.59	12.61	mm
-1.0 mm	8.96	7.35	11.55	11.58	mm
0.0 mm	8.35	6.85	9.74	9.81	mm
+1.0 mm	7.62	6.25	9.73	9.78	mm
+2.0 mm	6.84	5.61	8.75	8.78	mm
+3.0 mm	6.17	5.06	7.95	7.99	mm
+4.0 mm	5.5	4.51	7.11	7.13	mm

REPORTING: The following items shall be reported:

- Luminance threshold used, LMD entrance pupil position relative to last optical surface, positive and negative x-axis coordinates of eyebox, positive and negative y-axis coordinates of eyebox, and horizontal and vertical dimensions of the eyebox as shown in Table 1;
- The horizontal and vertical dimensions of the eyebox measured along the eyeline as shown in Table 2.



- Setup details, including LMD and aperture size, eye vantage point and any deviation of the eyeline relative to the DUT optical axis.

COMMENTS:

- (1) **Number of test points:** Generally, this measurement is performed by translating only along the x- and y- axes relative to the optical axis of the NED DUT. This test suite may be performed for several off axis points such as above and below (left and right) of the x- and y-axes to confirm the rectangular shape of the eyebox. However, typically, the shape may be inferred by the NED design and, possibly, by the rough alignment illustrated in Fig. 2.
- (2) **eye relief:** Not all NED devices offer an eye relief of 25 mm. Some may be less, and some may be more. Generally, the eye relief for any NED ranges from a minimum of 16 mm (common for normal prescription eyewear) to about 28 mm, allowing for the user's own prescription eyewear clearance.
- (3) **Measurement Distance:** If a less than or equal to 28 mm measurement is not achievable for a NED-LMD combination due to size of the aperture mounting or lens size, then it is not possible to use this particular NED-LMD combination.
- (4) **Influence of Eye Rotation:** As discussed in section 19.1, eye rotation vantage point is a critical factor in the measurement as it may affect the NED virtual image performance over angle and possibly change the effective NED FOV. If the NED eyebox is small (<10 mm), the eye rotation vantage point may significantly reduce the effective eyebox due to the additional displacement of the entrance pupil from the eye rotation.



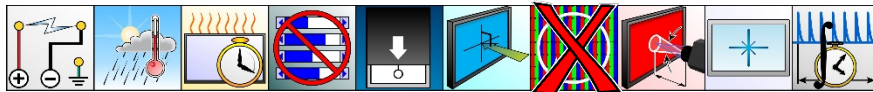
19.9.2 MICHELSON-CONTRAST METHOD

DESCRIPTION: This method determines the eyebox boundary by measuring the Michelson contrast at the center of the virtual image as the LMD entrance pupil is translated about the eye-point. The Michelson contrast threshold for determination of the eyebox dimensions is an absolute value, $0.0 \leq C_M \leq 1.0$. Typically, the threshold is 0.25 or, 0.50. The measured dimension of the eyebox will depend on the threshold value selected. For the procedure description that follows, a 0.50 threshold is used. However, it is important that the selected threshold value be agreed upon by all stakeholders and that the threshold value is clearly recorded in the test results. Also, note well that virtual image focal distance – the location of the virtual image in image space in front of the viewer – also may affect the determination of the eyebox dimensions. Depending on the design and application for the NED, the virtual image focal distance may be anywhere from approximately 15 inches to infinity. While the virtual image FOV may appear the same over this range, the eyebox measurements may vary – especially if the focal distance is less than about 1 meter. Maintaining the measurement location at the center of the virtual image while translating the LMD entrance pupil across the eyebox may require angular compensation – especially if the virtual image focal distance is small. The virtual image focal distance also shall be reported in the test results. Any angular compensation (θ , ϕ in degrees) needed also shall be reported in the test results.

APPLICATION: This measurement can be used for any NED or HUD. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

Caution: This method does not require that the entire field of view is above the required threshold value, only that the Michelson contrast at the center of the field of view remains above the Michelson contrast threshold. Therefore, this method generally overestimates the eyebox size than if the entire field of view is considered. Section 19.9.5 describes an alternative method that may produce more accurate results.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR EYEBOX MEASUREMENT – MICHELSON CONTRAST METHOD

The alignment method requires the use of a 2D LMD (see 19.2).

- At least a 5-axis motion apparatus is needed to scan over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. The setup using an array-type LMD and, as an example, an AR-type NED is shown in Fig. 1.
- Note: The procedure in this section is written for use with fully-manual mechanical motion devices. If a fully-automated system is available, consider using the procedure described in section 19.9.5.
- The eye rotation vantage point method (19.5) generally is used to scan over the virtual image FOV. In that case, the entrance pupil is placed at the eye-point and the LMD is pivoted about a position 10 mm behind it (to simulate eye gaze). Alternatively, the pupil rotation vantage point method (19.5) also can be used to scan the virtual image FOV but, this method neglects the impact of eye gaze.
- The measurement distance between the NED or HUD and the LMD should be specified by the manufacturer. However, this is often not defined. If the eye relief is not specified for an NED, it shall be assumed to be 25 mm (from the center of the last NED optical element to the vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- When using a 2D LMD, the LMD should have a photopic response, a 2 by 2 degree region of interest (measurement area), and it is useful to have a FOV that is larger than the virtual image. The 2D LMD should have background, flat field, and geometric corrections applied.
- The test pattern for this measurement is a Michelson contrast grille pattern with vertical or horizontal 1-pixel lines alternating on-off as illustrated in Fig. 2. If a > 0.50 Michelson contrast cannot be achieved in the virtual image center with this grille pattern, then a lower spatial frequency pattern should be used. See section 7.2 for recommendations for minimum grille resolution.

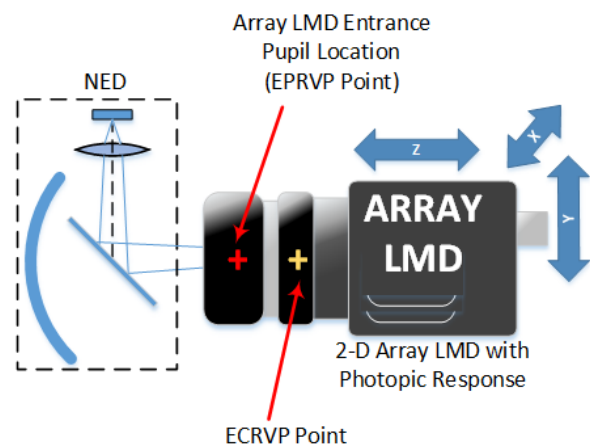


Fig. 1. Michelson contrast Method Setup
ECRVP: Eye Center Rotation Vantage Point.
EPRVP: eye pupil rotation vantage point



- The difference between the Michelson contrast measured at the center of the virtual image and the threshold value selected will affect the measured size of the eyebox. If the center reference Michelson contrast is only slightly higher than 0.5 and the threshold value selected is 0.5, the measured eyebox will be quite small. While a Michelson contrast near 1.0 typically is not achievable, a value > 0.8 is preferred. If the center reference Michelson contrast is near 0.5, a lower threshold value, perhaps 0.25, should be selected. Decreasing the spatial frequency of the grille test patterns also should increase the center reference Michelson contrast measured.

PROCEDURE, EYEBX CROSS-SECTION:

This procedure determines the cross-sectional eyebox dimensions at the reference eye-point based on the Michelson contrast at the center of the virtual image.

- Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the NED to be measured. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis (z-axis) or eyeline.
- Laterally position the LMD entrance pupil approximately in the center of the light field projected behind the NED.
- Render an alignment target (such as a crosshair) at the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
- Use the eye rotation vantage point method (19.5) to rotate the LMD FOV to the center of the virtual image.
- Present the desired test pattern for the eyebox measurement – such as the vertical 1-pixel on-off line pattern in Fig. 2.
- Capture an image of the test pattern with LMD near the center of the eyebox location. Using the capture tools, measure the Michelson contrast along 3 or more horizontal measurement lines (perpendicular to grille pattern) near the center of the captured image:

$$C_{MV} = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}, \text{ where}$$

$\overline{L_W}$ is the ensemble average of the light (white) measurements and $\overline{L_K}$ is the ensemble average of the dark (black) measurements.

- Switch to the horizontal grille pattern of the same spatial frequency. Capture an image of the test pattern with the LMD. Using the capture tools, measure the Michelson contrast along 3 or more vertical measurement lines (perpendicular to grille pattern) near the center of the captured image:

$$C_{MH} = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}, \text{ where}$$

$\overline{L_W}$ is the ensemble average of the light (white) measurements and $\overline{L_K}$ is the ensemble average of the dark (black) measurements.

- Translate the LMD in the -x direction while viewing and measuring the virtual image grille pattern Michelson contrast. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the negative x-axis position of the LMD where the virtual image contrast reaches a desired threshold value. The virtual image pattern may begin to fade at one edge as illustrated in Fig. 3a) as the LMD is translated. As the center Michelson contrast measurement decreases to the desired threshold level, the virtual image may appear similar to that shown in Fig. 3b) and the edge of the exit pupil may be visible at the edge of the virtual image. Record the LMD distance traveled from the eyepoint.

- Translate the LMD in the +x direction while viewing and measuring the virtual image grille pattern Michelson contrast. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the positive x-axis

position of the LMD where the virtual image Michelson contrast reaches the same threshold value. Record the LMD distance traveled from the eyepoint.

- Use the negative and positive x-axis boundary positions that produced the desired threshold value and calculate the x-axis dimension between those boundaries. Also calculate the approximate midpoint of the eyebox. Translate the LMD to that midpoint position and reset this as the new x=0 position.

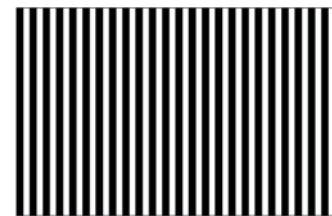


Fig. 2. 1 on/1 off grille test pattern.

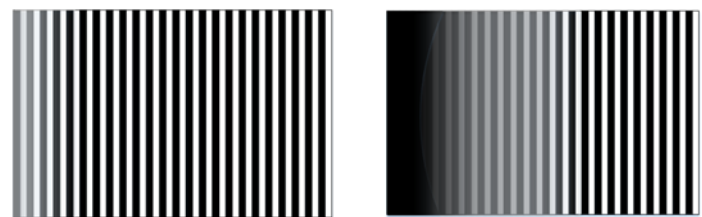


Fig. 3. a) Grille pattern Michelson contrast as LMD approaches the edge of the eyebox; b) As Center Michelson contrast approaches 0.5.



11. Switch to the horizontal line version of this pattern and repeat steps 8 – 10.
12. Translate the LMD in the + y direction while viewing and measuring the virtual image grille pattern. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the positive y-axis position of the LMD where the virtual image contrast reaches the same threshold value. Record the LMD distance traveled from the eyepoint.
13. Translate the LMD in the - y direction while viewing and measuring the virtual image grille pattern. Apply angular compensation as needed to maintain the LMD measurement field at the center of the virtual image. Determine the negative y-axis position of the LMD where the virtual image contrast reaches the same threshold value. Record the LMD distance traveled from the eyepoint.
14. Use the negative and positive y-axis boundary positions that produced the desired threshold value and calculate the y-axis dimension between those boundaries. Also calculate the approximate vertical midpoint of the eyebox. Translate the LMD to that mid-point position and reset this as the new y=0 position.
15. Switch back to the vertical line version of this pattern and repeat steps 12 – 14.
16. *Optional corner point measurement:* Repeat steps 8 through 15 to measure the x, y travel distances to the virtual image corners: upper left (UL), upper right (UR), lower left (LL) and, lower right (LR) and record LMD travel distances from the eyepoint.
17. Use the UL and LR boundary positions that produced the desired threshold value and calculate the back diagonal dimension between those boundaries. Use the UR and LL boundary positions that produced the desired threshold value and calculate the forward diagonal dimension between those boundaries. Also calculate the approximate vertical and horizontal midpoint of the eyebox. Translate the LMD to that mid-point position and reset this as the new x=y=0 position.
18. Repeat steps 8 to 15 (8 to 17 if corner point measurement option is selected) until the x-axis and y-axis mid-points are within 1 mm from the previous x=y=0 position (the origin for the NED DUT).
19. Record the absolute coordinates of the final eyebox horizontal and vertical dimensions and the mean width and height of the eyebox for the NED DUT as shown in Table 1, and the combined results based on the results from both vertical and horizontal grille patterns as shown in Table 2. Include the mean forward diagonal (FD) and back diagonal (BD) measurements if corner measurements option is selected, where FD is defined as UR + LL, BD is defined as UL + LR.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 1. Eyebox Data Example:

Center Michelson contrast Measurements with 0.50 Threshold

Device Description				NED Device 1				Left Ocular					
Parameter				Measured		Specification		Accept		Reject		Notes	
Michelson contrast center reference value				0.85		>0.8							
Michelson contrast edge threshold						≥ 0.50							
Grille pattern spatial frequency				1-pixel		1-pixel							
Eye relief (remember 3 mm Cornea offset)				25 mm		25 mm							
Pupil distance				28 mm		28 mm							
LMD-pupil diameter				5 mm		2-5 mm							
Measurement vantage point				Eye rotation		Eye rotation							
Measurement field angle				±1.0 degree		±1.0 degree							
Pointing direction alignment				Section 19.3.1									
Virtual Image Focal Distance				1 m		1 diopter							
Vertical Grille	Center			Translate Left		Translate Right		Translate Up		Translate Down			
Measurement Location	C_{MV}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)		
Virtual Image Center	0.85	0.0	0.0	-4.2	0.0	4.15	0.0	0.0	3.45	0.0	-3.4		
Angular Compensation (if needed)				θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)		
Measured (degrees, °)				0.23	0.0	-0.24	0.0	0.0	-0.2	0.0	0.19		
Δx (mm)				4.2		4.15							
Δy (mm)									3.45		3.4		
Mean horizontal eyebox (mm)				8.35									
Mean vertical eyebox (mm)								6.85					



Table 1. Continued											
Horizontal Grille	Center			Translate Left		Translate Right		Translate Up		Translate Down	
Measurement Location	C_{MH}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
Virtual Image Center	0.85	0.0	0.0	-4.1	0.0	4.2	0.0	0.0	3.4	0.0	-3.35
Angular Compensation (if needed)				θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)
Measured (degrees, °)				0.23	0.0	-0.24	0.0	0.0	-0.2	0.0	0.19
Δx (mm)				4.1		4.2					
Δy (mm)									3.4		3.35
Mean horizontal eyebox (mm)				8.3							
Mean vertical eyebox (mm)								6.75			
Optional Corner Measurements											
Vertical Grille	Center			Translate Upper Right		Translate Lower Left		Translate Upper Left		Translate Lower Right	
Measurement Location	C_{MV}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
Virtual Image Center	0.85	0.0	0.0	3.65	3.25	-3.65	-3.2	-3.7	3.3	3.6	-3.25
Angular Compensation (if needed)				θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)
Measured (degrees, °)				-0.21	-0.19	-0.21	-0.19	0.21	-0.19	-0.21	0.19
Δx (mm)				3.65		3.65		3.7		3.6	
Δy (mm)					3.25		3.2		3.3		3.25
Mean forward diagonal eyebox (mm)				9.74							
Mean back diagonal eyebox (mm)								9.81			
Optional Corner Measurements											
Horizontal Grille	Center			Translate Upper Right		Translate Lower Left		Translate Upper Left		Translate Lower Right	
Measurement Location	C_{MH}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
Virtual Image Center	0.85	0.0	0.0	3.6	3.25	-3.65	-3.2	-3.7	3.35	3.6	-3.25
Angular Compensation (if needed)				θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)	θ (°)	φ (°)
Measured (degrees, °)				-0.21	-0.19	-0.21	-0.19	0.21	-0.19	-0.21	0.19
Δx (mm)				3.6		3.65		3.7		3.6	
Δy (mm)					3.25		3.2		3.35		3.25
Mean forward diagonal eyebox (mm)				9.70							
Mean back diagonal eyebox (mm)								9.84			

Note (as in section 19.9.1) that the above procedure measures the height and width (or, diagonal) of the exit pupil or, the height and width (or, diagonal) of the eyebox at the location of the eye-point. The depth range of the eyebox also shall be determined. To accomplish this, first, the *eyeline* must be established. Generally, it may be assumed that the eyeline is coincident with the optical axis of the NED. However, this may not always be the case. To establish the eyeline, the LMD should be moved away from the eye-point position along the z-axis for some distance. This distance may be a few millimeters. If the image of the grille pattern begins to deteriorate around the edges due to vignetting or, the Michelson contrast in the center of the pattern decreases below 0.50, then LMD has been moved too far. Slowly move the LMD back toward the eye-point until the edges of the grille pattern are just discernable, if, perhaps, a little fuzzy (i.e., slightly out of focus) or, the Michelson contrast in the center of the pattern has not decreased to less than 0.50. Repeat the above procedure, steps 6 through 15 or, follow the procedure in Section 19.3, to locate the eye-point. If the new eye-point location remains at $x = y = 0.0$, then the eyeline coincides with the NED optical axis. If the new eye-point is located at $x \neq y \neq 0.0$, then the eyeline is not coincident with the optical axis of the NED. In this case, use the θ and φ goniometer adjustments for the NED to align the eyeline to the z-axis of the LMD.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 2. Eyebox Data Example:

Determine Minimum Eyebox Height, Width and Diagonals from Horizontal and Virtual Grille Measurements

Translation Direction	Translate Left		Translate Right		Translate Up		Translate Down	
Travel distances	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
Vertical Grille Results	-4.2	0.0	4.15	0.0	0.0	3.45	0.0	-3.4
Horizontal Grille Results	-4.1	0.0	4.2	0.0	0.0	3.4	0.0	-3.35
Minimum Δx (mm)	4.1		4.15					
Minimum Δy (mm)						3.4		3.35
Minimum horizontal eyebox (mm)	8.25							
Minimum vertical eyebox (mm)					6.75			
Corner Point Measurements	Upper Right		Lower Left		Upper Left		Lower Right	
Travel distances	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
Vertical Grille Results	3.65	3.25	-3.65	-3.2	-3.7	3.3	3.6	-3.25
Horizontal Grille Results	3.6	3.25	-3.65	-3.2	-3.7	3.35	3.6	-3.25
Minimum Δx (mm)	3.6		3.65		3.7		3.6	
Minimum Δy (mm)		3.25		3.2		3.3		3.25
Minimum Forward Diagonal (mm)	9.7							
Minimum Back Diagonal (mm)					9.81			

PROCEDURE, EYEBOX VOLUME:

This procedure determines the three-dimensional eyebox about the reference eye-point based on the virtual image center Michelson contrast.

1. Move the LMD back to the position of the original eye-point.
2. Move the LMD in small steps, perhaps 1 mm, away from the original eye-point and repeat the eyebox cross-section procedure, steps 6 – 15, at each step position until reaching the point where the grille pattern edges begin to deteriorate.
3. Record the results for each step position in a table similar to Table 1, above.
4. Move the LMD back to the original eye-point location and then move the LMD closer to the NED in small steps of the same size used when moving the LMD away from the eye-point.
5. Repeat the eyebox cross-section procedure above, steps 6 – 15, for each step position and record the results in tables such as Table 1.
6. Continue this process until a reasonable inside distance has been reached, such as a minimum eye relief distance of 21 mm (+3 mm, corneal thickness.)
7. *Optional corner point measurement:* Repeat the above procedure steps 2 – 6 for the corner points: UL, UR, LL and, LR.
8. Use the results to calculate the minimum eyebox height, width, forward and back diagonals from both the mean vertical and horizontal grille results from Table 2 as shown in Table 3.



—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Table 3. Data Example: Eyebow dimension along z-axis					
Device Description	NED Device 1		Left Ocular		
Parameter	Measured	Specification	Accept	Reject	Notes
Michelson contrast center reference value	0.85	>0.80			
Michelson contrast edge threshold		> 0.50			
Grille pattern spatial frequency	1-pixel	1-pixel			
Eye relief (3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
LMD pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	±1.0 degree	±1.0 degree			
Pointing direction alignment	Section 19.3.1				
Virtual Image Focal Distance	1 m	1 diopter			
Eyeline Position (relative to Eye-point)	Mean Horizontal Eyebow Dimension	Mean Vertical Eyebow Dimension	Mean Forward Diagonal Dimensions	Mean Back Diagonal Dimensions	Units
-4.0 mm	11.32	9.29	14.59	14.62	mm
-3.0 mm	10.61	8.70	13.65	13.71	mm
-2.0 mm	9.75	8.00	12.59	12.61	mm
-1.0 mm	8.96	7.35	11.55	11.58	mm
0.0 mm	8.35	6.85	9.74	9.81	mm
+1.0 mm	7.62	6.25	9.73	9.78	mm
+2.0 mm	6.84	5.61	8.75	8.78	mm
+3.0 mm	6.17	5.06	7.95	7.99	mm
+4.0 mm	5.5	4.51	7.11	7.13	mm

REPORTING: The following items shall be reported:

- Michelson contrast threshold used, LMD entrance pupil position relative to last optical surface, positive and negative x-axis coordinates of eyebow, positive and negative y-axis coordinates of eyebow, and horizontal and vertical dimensions of the eyebow as shown in Table 1.
- The horizontal and vertical dimensions of the eyebow measured along the eyeline as shown in Table 2.
- Setup details, including LMD and aperture size, eye vantage point and any deviation of the eyeline relative to the DUT optical axis.
- Grille pattern spatial frequency.

COMMENTS:

- 1) **Number of test points:** Generally, this measurement is performed by translating only along the x- and y- axes relative to the optical axis of the NED DUT. This test suite may be performed for several off axis points such as above and below (left and right) of the x- and y-axes to confirm the rectangular shape of the eyebow. However, typically, the shape may be inferred by the NED design and, possibly, also by the rough alignment illustrated in Fig. 4 in section 19.9.1.
- 2) **eye relief:** Not all NED devices offer an eye relief of 25 mm. Some may be less and some may be more. Generally, the eye relief for any NED ranges from a minimum of 16 mm (common for normal prescription eyewear) to about 28 mm, allowing for the user's own prescription eyewear clearance.
- 3) **Measurement Distance:** If a less than or equal to 28 mm measurement is not achievable for a NED-LMD combination due to size of the aperture mounting or lens size, then it is not possible to use this particular NED-LMD combination.
- 4) **Influence of Eye Rotation:** As discussed in section 19.1, Eye Rotation Vantage Point is a critical factor in the measurement as it will affect the NED virtual image performance over angle and change the effective NED FOV. If the NED eyebow is small (<10 mm), the Eye Rotation Vantage Point may significantly reduce the effective eyebow due to the additional displacement of the entrance pupil from the eye rotation.



19.9.3 DRAPER METHOD

DESCRIPTION: The Luminance method and the Michelson contrast method described in the previous sections have been used to measure the dimensions of the eyebox for NEDs for some time, providing accurate measurements of the eyebox¹. However, as may be assessed from the procedures described in these sections, these methods are data intensive and may be quite time-consuming to implement. For example, in section 19.9.2, describing the Michelson contrast method, the measurement of each cross-section of the eyebox requires at least 12 image captures – six for width measurement and six for height measurement (not including corner points.) If the number of cross-sections measured is as described in section 19.9.2, four on either side of the eye-point along the eyeline, then, 108 image captures are required. Additionally, as each image capture requires contrast be measured along at least three lines perpendicular to the grille pattern lines, a total of 324 contrast measurements must be made. Recent efforts published jointly by the CERDEC Night Vision Electronic Sensors Directorate and NIST² describe a new method, called the Draper Method, that greatly reduces the number of image captures required and the amount of post-processing computations. The method may be used with either luminance (full-field white pattern) or contrast (1-pixel wide grille pattern) or, a combination. The entire eyebox volume may be mapped with as few as *two* image captures. This number increases only by one for each eyebox parameter measured (e.g., luminance, contrast, distortion.)

APPLICATION: This measurement can be used for any NED or HUD. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

THEORY: The theory underlying this method can be explained as follows: Consider an NED with an arbitrary shaped pupil in linear coordinates and an arbitrary shaped field stop in angle coordinates. A ray may be found that originates at the field boundary, just grazes the NED pupil and, intersects the optical axis or eyeline. The triangular area enclosed by the ray, eyeline and, the display exit pupil is a 2-dimensional region that may be described as the “useable eye area in the plane of the boundary ray and the eyeline,” as shown in Fig. 1. These triangular areas may be created arbitrarily close by increasing the density of rays traced from the field boundary to the eyeline. The useable eye volume (eyebox) then is formed by the volume enclosed by these rays traced from the field boundary as shown in Fig. 2. The full display will be visible to the user as long as the eye pupil is placed anywhere within the volume created by the compilation of these triangular areas. The density of pupil-limited field boundary

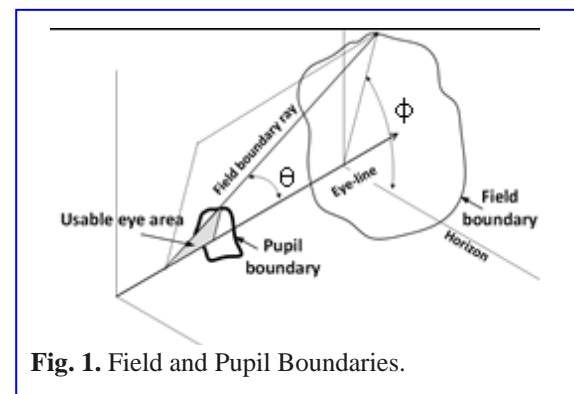


Fig. 1. Field and Pupil Boundaries.

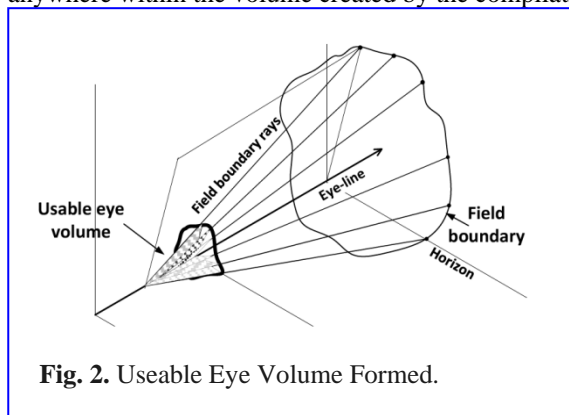


Fig. 2. Useable Eye Volume Formed.

$$h(\varphi) = Z * \tan \alpha(\varphi)$$

$$PD = \frac{h(\varphi)}{\tan \theta(\varphi)}$$

The analysis used to determine PD and h is repeated for as many φ planes as are needed to adequately approximate the volume.

Similar to the horizontal and vertical scans of the eyebox described in sections 19.9.1 and 19.9.2, the size of the LMD entrance pupil will impact the accuracy of the result. For this method, the entrance pupil affects the depth of field of the LMD. The LMD entrance pupil should be chosen to maximize the depth of field without limiting the resolution by diffraction.

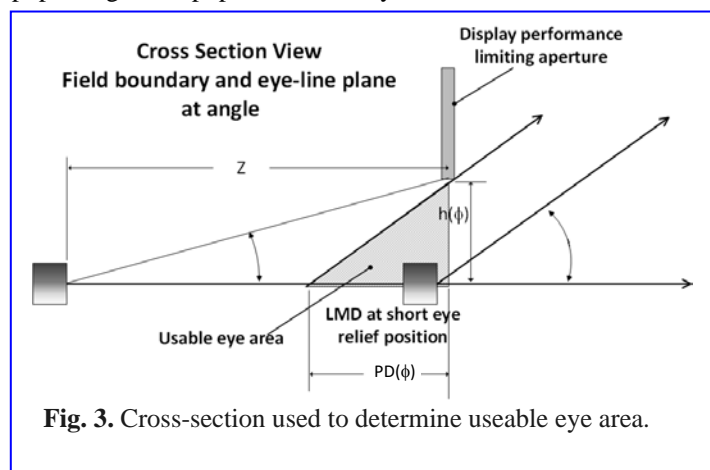


Fig. 3. Cross-section used to determine useable eye area.

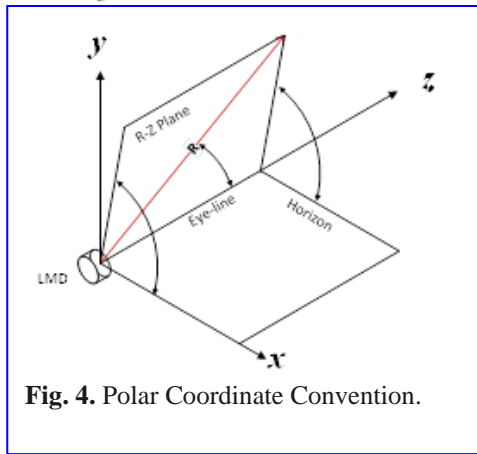


Fig. 4. Polar Coordinate Convention.

: The captured images are analyzed first by finding a sufficiently dense sampling of the pixel coordinates of the field and pupil boundaries using the image captures at the short and long pupil distance, respectively. The LMD's optical characterization mapping of camera pixel coordinates to angle space is then used to find the angular coordinates for the pixel x , y array of boundary data for the field and pupil boundaries. Note that the data analysis is simpler and more robust if the angular coordinate system is polar with the eye-line being the $(0,0)$ polar coordinate as illustrated in Fig. 4.

Once the angle coordinates of the field and pupil boundaries are determined, the azimuthal angle ϕ is used as the independent variable and the inclination angle θ as the dependent variable to create a simple linear interpolation function that describes the angular subtense of the pupil boundary $\alpha(\phi)$ and the angular subtense of the field boundary $\theta(\phi)$.

The useable eye volume or, the region of unvignetted FOV, may be readily computed for almost any desired resolution in pupil distance and ϕ

angle about the eye-line. The result then may be presented in a form which best enables the visualization of the usable eye volume shape. Figure 5 illustrates the results for the eyebox dimensions at several locations along the eyeline from the field to the pupil as measured using the Michelson contrast method and shows the decreasing size of the eyebox as the pupil distance increases. Figure 6 shows an example 3D plot of an eyebox determined using the luminance method.

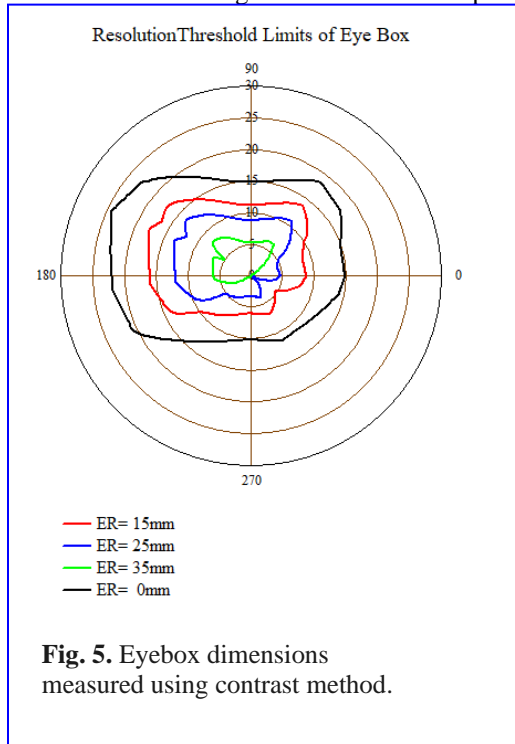


Fig. 5. Eyebox dimensions measured using contrast method.

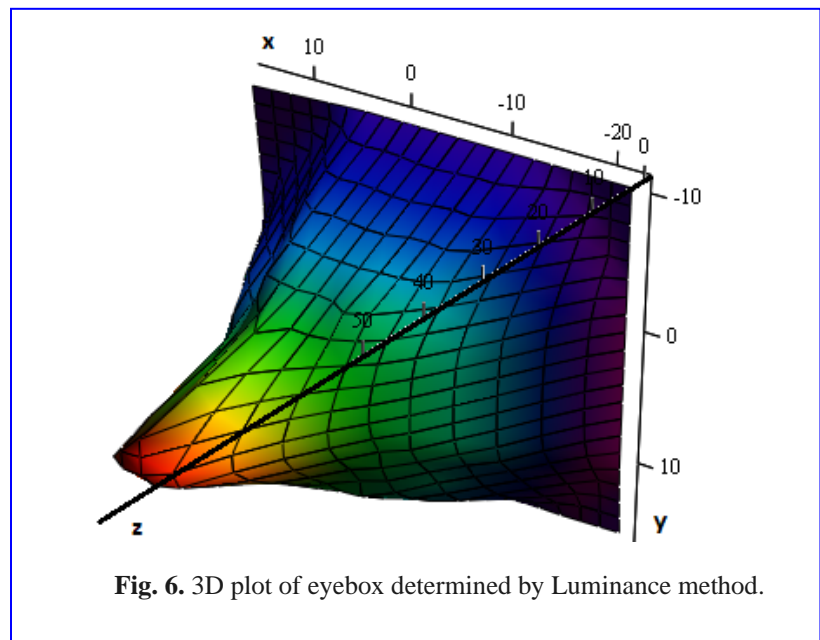
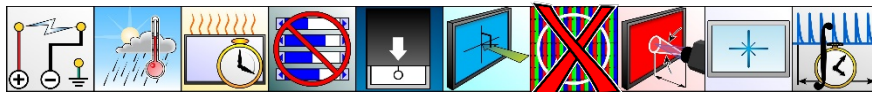


Fig. 6. 3D plot of eyebox determined by Luminance method.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR EYEBOX MEASUREMENT – DRAPER METHOD

The alignment method can be used with a spot-type or 2D LMD (see 19.2). However, performance of the Draper method procedure requires a 2D LMD.

- A 5-axis motion apparatus for the LMD is not required for this procedure but, it would be nice to have available if necessary or for fine alignment. Azimuth and Elevation nested goniometer motion is required for the NED DUT as described in the following procedure. The goniometer center of rotation should be the eye-point position at the nominal exit pupil distance (eye relief +3 mm corneal thickness.) The setup using a 2D LMD and, as an example, an AR-type NED is shown in Fig. 7.
- The eye center rotation vantage point method (19.5) is generally used to scan over the virtual image FOV. In that case, the entrance pupil is placed at the eye-point and the LMD is pivoted about a position 10 mm behind it (to simulate eye gaze).



Alternatively, the pupil rotation vantage point method (19.5) also can be used to scan the virtual image FOV but, this method neglects the impact of eye gaze.

The measurement distance between the NED and the LMD should be specified by the manufacturer. However, this is often not defined. If the eye relief is not specified, it shall be assumed to be 25 mm (from the center of the last NED optical element to vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.

Note: As shown in Fig. 7, the last optic element is a 45° partial mirror, the lower right edge of which determines the location where the eye relief is zero.

- When using a 2D LMD, the LMD should have a photopic response, and it should have a FOV that is larger than the virtual image. The 2D LMD should have background, flat field, and geometric corrections applied.
- A rough visual alignment of the LMD can be made by placing the LMD entrance pupil at the approximate center of the light field projected behind the NED, see Fig. 4 in section 19.9.1.
- This method also depends on the following measurement system conditions:
 - 1) The LMD system must be characterized with image plane pixel coordinates converted to angle space coordinates;
 - 2) The LMD array camera FOV exceeds the FOV of the display to be measured and;
 - 3) The LMD system must be capable of being translated along the display eye-line to two positions: a short eye-relief position in which the display system full FOV can be captured by the LMD without vignetting, and a long pupil distance position in which all of the field boundary edges are obscured or aberrated by the display pupil.
- In addition, as an imaging LMD measurement, it is limited to measurements that do not require significant eye rotation (and subsequent pupil offset.)

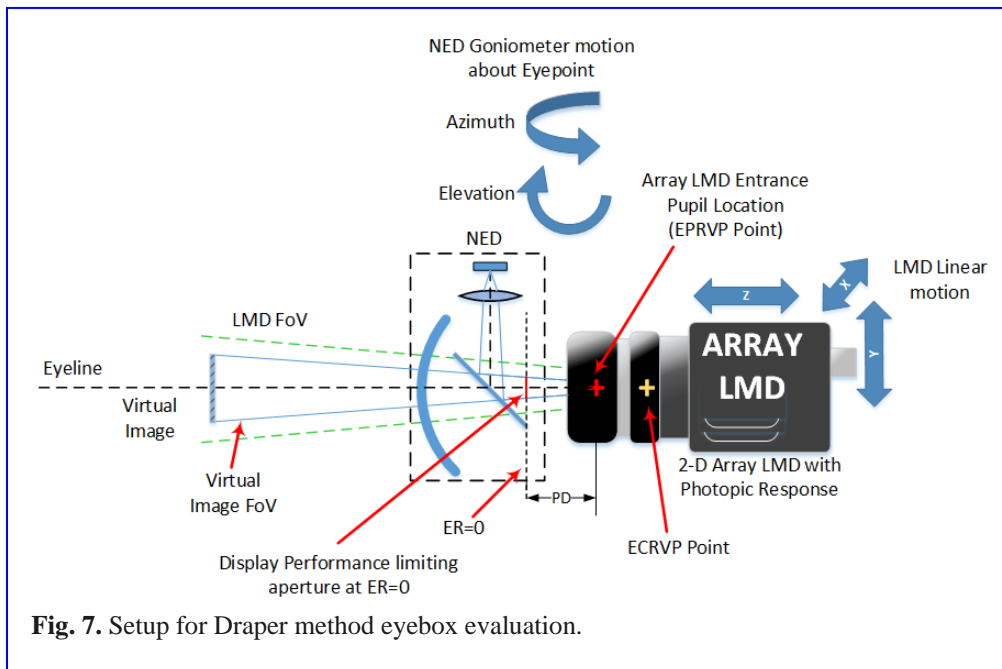


Fig. 7. Setup for Draper method eyebox evaluation.

PROCEDURE:

Initial Measurements:

Note: The Draper method does not require the same test pattern for every step. For example, the full-field white pattern (luminance method) may be used for initial measurements while the 1-pixel wide grille pattern may be used for the Draper measurements.

1. Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the NED to be measured. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis (z-axis) or eyeline.
2. Laterally position the LMD entrance pupil approximately in the center of the light field projected behind the NED.
3. Render an alignment target (such as a crosshair) as the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
4. Use the eye rotation vantage point method (19.5) to rotate the LMD FOV to the center of the virtual image.
5. Present the desired test pattern for the eyebox measurement – such as the vertical 1-pixel on-off line pattern in Fig. 2 of section 19.9.2.
6. Capture an image of the test pattern with LMD near the center of the eyebox location. Using the capture tools, measure the Michelson contrast along 3 or more horizontal lines near the center of the captured image:



$$C_M = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}, \text{ where}$$

$\overline{L_W}$ is the ensemble average of the light (white) measurements and $\overline{L_K}$ is the ensemble average of the dark (black) measurements.

7. Laterally translate the LMD to the left while viewing and measuring the virtual image grille pattern. Determine the negative x-axis position of the LMD where the virtual image contrast reaches a desired threshold value. The virtual image pattern will begin to fade at one edge as illustrated in Fig. 3 in section 19.9.2.
8. Laterally translate the LMD to the right while viewing and measuring the virtual image grille pattern. Determine the positive x-axis position of the LMD where the virtual image contrast reaches the same threshold value.
9. Use the negative and positive x-axis boundary positions that produced the desired threshold value and calculate the x-axis dimension between those boundaries. Also calculate the approximate midpoint of the eyebox. Translate the LMD to that midpoint position and reset this as the new x=0 position.
10. Switch to the horizontal line version of this pattern.
11. Laterally translate the LMD up while viewing and measuring the virtual image grille pattern. Determine the positive y-axis position of the LMD where the virtual image contrast reaches the same threshold value.
12. Laterally translate the LMD down while viewing and measuring the virtual image grille pattern. Determine the negative y-axis position of the LMD where the virtual image contrast reaches the same threshold value.
13. Use the negative and positive y-axis boundary positions that produced the desired threshold value and calculate the y-axis dimension between those boundaries. Also calculate the approximate vertical midpoint of the eyebox. Translate the LMD to that mid-point position and reset this as the new y=0 position.
14. Repeat steps 6 to 13 until the x-axis and y-axis mid-points are within 1 mm from the previous x=y=0 position (the origin for the NED DUT).
15. Readjust the LMD focus as needed.
16. Record the absolute coordinates of the final eyebox horizontal and vertical dimensions and the mean width and height of the eyebox at the eye-point location for the NED DUT.

Establishing the eyeline:

Generally, it may be assumed that the eyeline is coincident with the optical axis of the NED. However, this may not always be the case.

1. Move the LMD away from the eye-point position along the z-axis in the positive direction for some distance. This distance may be a few millimeters. If the image of the 1-pixel wide grille pattern begins to deteriorate around the edges due to vignetting or, the contrast in the center of the pattern decreases below 0.5, then LMD has been moved too far. Slowly move the LMD back toward the eye-point until the edges of the 1-pixel wide grille pattern are just discernable, if, perhaps, a little fuzzy (i.e., slightly out of focus) or, the contrast in the center of the pattern has not decreased to less than 0.5.
2. Repeat the above procedure, steps 6 through 13 or, follow the procedure in Section 19.3, to locate the eye-point. If the new eye-point location remains at x = y = 0.0, then the eyeline coincides with the NED optical axis.
3. If the new eye-point is located at x ≠ y ≠ 0.0, then the eyeline is not coincident with the optical axis of the NED. In this case, use the Elevation and Azimuth goniometer adjustments for the NED to rotate the NED about the original eye-point to align the eyeline to the z-axis of the LMD.

Draper Method Procedure:

1. Move the LMD in the negative direction along the eyeline to a point well within the eye relief range. For example, if the eye relief is specified at 25 mm, move the LMD such that the LMD entrance pupil is within about 5 – 10 mm of the ER=0 plane.
2. Focus the LMD on the virtual image and capture images of the both the vertical and horizontal grille patterns. This is the “Short pupil distance.”
3. Move the LMD in the positive direction along the eyeline to a point well beyond the original eye-point position where all of field boundary edges are obscured or aberrated by the display pupil. This distance may be more than 100 mm beyond the original eye-point position.
4. Focus the LMD on the virtual image and capture images of the both the vertical and horizontal grille patterns. This is the “long pupil distance.”

ANALYSIS:

- The captured images are analyzed first by finding a sufficiently dense sampling of the pixel coordinates of the field and pupil boundaries using the image captures at the short and long pupil distance, respectively. Note: the pixel coordinate density may be limited in the long pupil distance captured image by the relative size of the captured pupil and the pixel density of the LMD.
- Use the edge finding capability of your image processing tool to automate this process.
- The LMD's optical characterization mapping of camera pixel coordinates to angle space is then used to find the angular coordinates for the pixel x, y array of boundary data for the field and pupil boundaries. This is where the use of a cylindrical coordinate system with the center axis being the eyeline (as shown in Fig. 4) is useful in reducing the



computation complexity. Note: The field height at the ER=0 plane in the captured images and in Fig. 7, is $2 \cdot h$ as shown in Fig 3. In the cylindrical coordinate system, h is positive above the X=0 plane and negative below it.

- Once the angle coordinates of the field and pupil boundaries are determined, the azimuthal angle ϕ is used as the independent variable and the inclination angle θ as the dependent variable to create a simple linear interpolation function that describes the angular subtense of the pupil boundary $\alpha(\phi)$ and the angular subtense of the field boundary $\theta(\phi)$ as shown in Fig. 8.

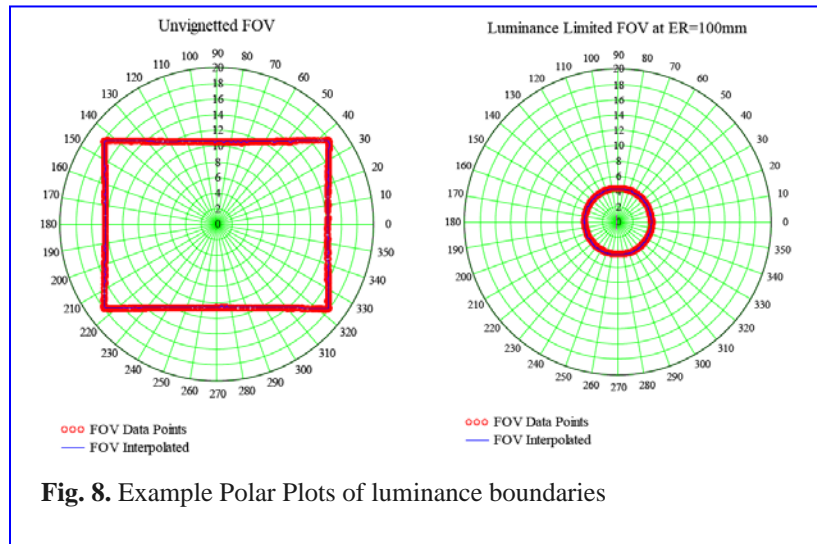


Fig. 8. Example Polar Plots of luminance boundaries

- The useable eye volume, or the region of unvignetted FOV, can be readily computed for almost any desired resolution in pupil distance and ϕ angle about the eyeline using the equations,

$$h(\phi) = Z * \tan \alpha(\phi)$$

$$PD = \frac{h(\phi)}{\tan \theta(\phi)}$$

- For example, Fig. 5 above illustrates the results for the eyebox dimensions where ER=0 mm, 15 mm, 25 mm and, 35mm, along the eyeline from the field to the pupil as measured using the Michelson contrast method and shows the decreasing size of the eyebox as the pupil distance increases.
- The angular subtense of the pupil at various PD along the eyeline can be converted from angular space to linear space (see Fig. 4) to obtain the linear dimensions of the eyebox. The linear dimensions should be as measured along the horizontal and vertical meridional lines.

REPORTING: The following items shall be reported:

- Michelson contrast threshold used.
- The horizontal and vertical linear dimensions of the eyebox measured along the eyeline as shown in Table 1.
- Setup details, including LMD and aperture size, eye vantage point and DUT optical axis.
- Deviation, if any, of the eyeline from the NED optical axis in θ and ϕ in degrees.

—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Table 1. Data Example: Eyebox dimension along Eyeline			
eye relief Distance (mm)	Horizontal Eyebox Dimension	Vertical Eyebox Dimension	Units
0.0 mm	35.142	25.535	mm
15.0 mm	23.662	17.528	mm
25.0 mm	14.497	12.671	mm
35.0 mm	6.433	7.513	mm

- The Eyebox dimensional data in Table 1 also may be shown graphically as illustrated in Fig. 9 showing the meridional height and width of the eyebox as measured at several eye relief distances.

COMMENTS:

- Number of test points:** This measurement procedure requires only a few image captures to provide sufficient information to determine the eyebox dimensions at several positions along the eyeline. However, as is illustrated in Fig. 8, many data points are required to accurately represent the eyebox volume over the region of interest. The accuracy of



the results of this method – especially in describing the shape of the eyebox as aberrations occur – requires a large number of data points be collected.

- 2) **Eye relief:** Not all NED devices offer an eye relief of 25 mm. Some may be less and some may be more. Generally, the eye relief for any NED ranges from a minimum of 16 mm (common for normal prescription eyewear) to about 28 mm, allowing for the user's own prescription eyewear clearance. This measurement procedure requires a nominal eye relief either be known or, assumed, for reference.
- 3) **Center of Rotation for Off-Axis Measurements:** This measurement method does not require off-axis measurements through the vantage point of the eye pupil. However, eye rotation or, pupil rotation points may be used to verify alignment of the LMD entrance pupil to the NED optical axis.

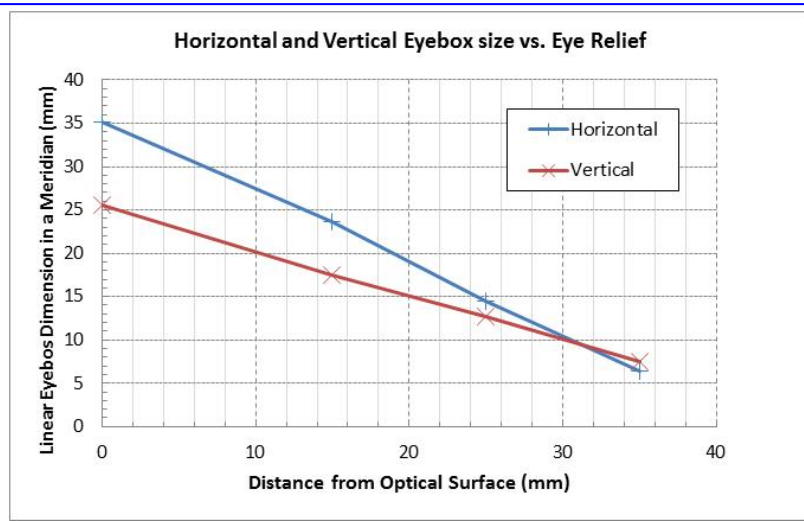


Fig. 9. Example Plot of Linear Eyebox Dimensions

REFERENCES:

- ¹ Draper, R. S., Penczek, J., Varshneya, R., and Boynton, P. A., "Standardizing Fundamental Criteria for Near Eye Display Optical Measurements: Determining Eye Point Position," *SID DIGEST*, p. 961, 2018.
- ² Varshneya, R., Draper, R. S., Penczek, J., Pixton, B. M., Nicholas, T. F., and Boynton, P. A., "Standardizing Fundamental Criteria for Near Eye Display Optical Measurements: Determining the Eye-box," 2020.



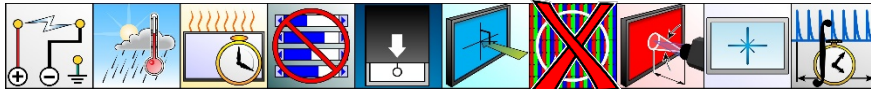
19.9.4 LUMINANCE-BASED FIELD OF VIEW METHOD

DESCRIPTION: The methods described in this section and the section that follows use the virtual image field of view (FOV) as the reference for measuring the extent of the eyebox. The procedure below resembles the procedure described in section 6.8 of the IEC standard, IEC 63145-20-10-2019¹ while incorporating elements of the procedure described in section 19.8 to measure the angular dimensions of the virtual image FOV. Compared to section 19.9.1 above, this method requires more measurements to obtain the dimensions of the eyebox but, the results may be more applicable as the visible (useable) FOV defines the practical dimensions of the eyebox (see the Terminology section of section 19.0.) If the test setup used to measure the characteristics of the NED or HUD is fully manual, the method of section 19.9.1 may be easier to perform, but likely will overestimate the eyebox compared to the procedure described here. .

The luminance threshold for determination of the eyebox dimensions generally is a percentage of the center luminance as measured with the center of the LMD entrance pupil located at the eye-point. Typically, the threshold is 25% or, 50%. The measured dimension of the eyebox will depend on the threshold percentage selected. For the procedure description that follows, a 50% threshold is used. However, it is important that the selected threshold percentage be agreed upon by all stakeholders and that the threshold percentage is clearly recorded in the test results. Also, note well that virtual image focal distance – the location of the virtual image in image space in front of the viewer – also may affect the determination of the eyebox dimensions. Depending on the design and application for the NED, the virtual image focal distance may be anywhere from approximately 15 inches to infinity or, may cover a similar range if the NED is capable of supporting multiple focal planes as in light-field technology devices. While the virtual image FOV may appear the same over this range, the eyebox measurements may vary – especially if the focal distance is less than about 1 meter. The virtual image focal distance (or, range) shall be reported in the test results.

APPLICATION: This measurement can be used for any near-eye display. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR FIELD OF VIEW MEASUREMENT

A spot type LMD with viewport or 2D LMD according to 19.2 shall be used to measure the important characteristics of the NED virtual image. All evaluations are performed within a measurement field angle of ± 1 degree around the optical axis of the LMD. If another measurement field angle is used it shall be reported.

- At least a 5-axis motion apparatus is needed to scan over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. The setup using a spot-type LMD and, as an example, an AR-type NED is shown in Fig. 1 of section 19.9.1 above.
- The eye center rotation vantage point method (19.5) generally is used to scan over the virtual image FOV.
- The measurement distance between the NED and the LMD should be specified by the manufacturer. However, this is often not defined. If the eye relief is not specified for an NED, it shall be assumed to be 25 mm (from the center of the last NED optical element to the vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- For a spot-type LMD, the measurement field angle (aperture) is typically 2 degrees ($\pm 1^\circ$). When using the spot-type LMD, it is valuable also to view the 2D virtual image around the measurement field angle.
- When using a 2D LMD, the LMD should have a photopic response, a ± 1 degree region of interest (measurement area), and it is useful to have a field of view that is larger than the virtual image. The 2D LMD should have background, flat field, and geometric corrections applied.
- The test pattern for this measurement is a full-field white pattern. An alignment pattern that may be used is illustrated in Fig. 1 below. This pattern is similar to the one used in section 19.8 to measure the virtual image FOV.
- A rough visual alignment of the LMD may be made by placing the LMD entrance pupil at the approximate center of the light field projected behind the NED, see Fig. 2 of section 19.9.1.
- A goniometric motion apparatus is needed to scan over a range of viewing directions using the reference eye center rotation vantage point method.
- The center of the virtual image is measured and provides the reference value to calculate the edge threshold value. For uniformity measurements, the five and nine positions illustrated in Fig. 1 are recommended. In the five position measurement case, the center point is number 5 and the corner points are 1, 3, 7, and 9, from upper left to bottom right. A 25-point alignment pattern also may be used as shown in Section 19.8, Fig. 1.
- This test method **requires** prior measurement of the angular dimensions of the virtual image FOV as described in section 19.8 as some or, all of the FOV points will be needed in the following procedure.



PROCEDURE, EYEBOX CROSS-SECTION:

The following procedure is recommended for this measurement.

1. a) Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the NED to be measured. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis (z-axis) or eyeline.
b) Laterally position the LMD entrance pupil approximately in the center of the light field projected behind the NED (see 19.3 and Fig. 2 in section 19.9.1).
c) Render an alignment target (such as a crosshair) at the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
d) Use the eye center rotation vantage point method (19.5) to rotate the LMD field of view to the center of the virtual image.
2. Using the measured FOV points from the prior FOV test, as described in section 19.8, determine the 9 points (in this example but, may be 5 or 25 also) by calculating the angular field positions (θ, ϕ in degrees) 10% inside (toward the FOV center) the FOV measurements points. These are the new 9 measurement points for this test method as indicated by the inward pointing arrows in Fig. 2.
3. a) Using the θ and ϕ goniometer adjustments direct the pointing of the LMD to point 5.
b) Present the desired test pattern for the eyebox measurement – generally a full-field white pattern.
c) Measure the luminance at this point. This is the center luminance reference for this evaluation.
4. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the left-side point 4. Refocus the LMD on this point.
b) Laterally translate the LMD to the left. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the negative x-axis position (Δx_{41}) of the LMD where the virtual image luminance reaches a desired threshold value (for example, 25% or 50 % of the luminance at the center). The virtual image pattern will begin to fade at one edge as illustrated in Fig. 3 in section 19.9.1. Make sure the edge of the virtual image remains clearly visible.
5. a) Laterally translate the LMD to the right. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the positive x-axis position (Δx_{61}) of the LMD where the virtual image luminance reaches the same desired threshold value.
b) Translate the LMD back to the origin and then translate it up toward point 2. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the positive y-axis position (Δy_{21}) of the LMD where the virtual image luminance reaches the same desired threshold value.
c) Translate the LMD down toward point 8. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the negative y-axis position (Δy_{81}) of the LMD where the virtual image luminance reaches the same desired threshold value.
d) Record the ($\Delta x_{11}, \Delta y_{11}$) for all positions.
6. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
7. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the right-side point 6. Refocus the LMD on this point.
b) Laterally translate the LMD to the left while viewing and measuring the virtual image luminance. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *right-side* point. Determine the positive x-axis position (Δx_{42}) of the LMD where the virtual image luminance reaches the same threshold value.
8. Repeat step 5 while maintaining pointing toward the *right-side* point 6. Determine the positions for $\Delta x_{62}, \Delta y_{22}$ and, Δy_{82} . Record the ($\Delta x_{i2}, \Delta y_{i2}$) for all positions.

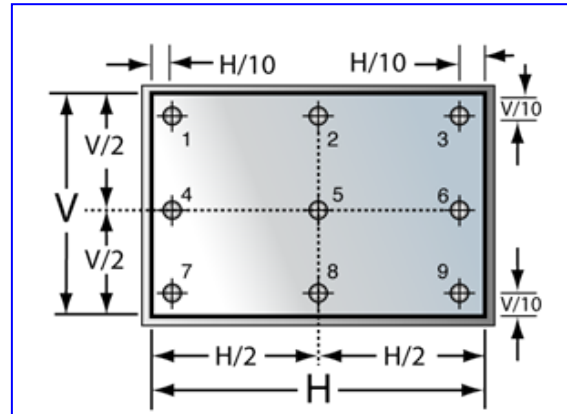


Fig. 1. Measurement locations using 9 positions (locations 1 to 9), or 5 positions (locations 1,3,5, 7, and 9).

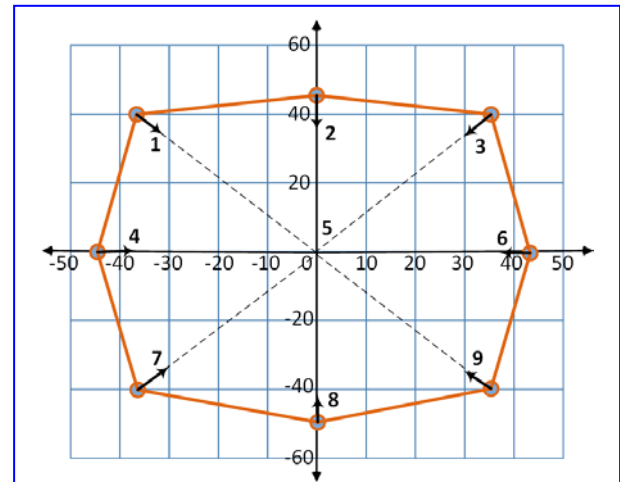


Fig. 2. Measurement locations using 9 positions based on prior FoV angular measurements



9. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
 10. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the *top*-side point 2. Refocus the LMD on this point.
b) Laterally translate the LMD to the left while viewing and measuring the virtual image luminance. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *top*-side point. Determine the positive x-axis position (Δx_{43}) of the LMD where the virtual image luminance reaches the same threshold value.
 11. Repeat step 5 while maintaining pointing toward the *top*-side point 2. Determine the positions for Δx_{63} , Δy_{23} and, Δy_{83} . Record the (Δx_{i3} , Δy_{i3}) for all positions.
 12. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
 13. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the *bottom*-side point 8. Refocus the LMD on this point.
b) Laterally translate the LMD to the left while viewing and measuring the virtual image luminance. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *bottom*-side point. Determine the positive x-axis position (Δx_{44}) of the LMD where the virtual image luminance reaches the same threshold value.
 14. Repeat step 5 while maintaining pointing toward the *bottom*-side point 8. Determine the positions for Δx_{64} , Δy_{24} and, Δy_{84} . Record the (Δx_{i4} , Δy_{i4}) for all positions.
- Optional: Steps 15 and 16 using the corner points 1, 3, 7 and, 9 as reference points.*
15. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
 16. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the corner points, 1, 3, 7 and, 9, in succession, refocusing the LMD on each corner point.
b) For each corner point, laterally translate the LMD to the left while viewing and measuring the virtual image luminance. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *corner* point. Determine the x-axis position (Δx_{4j} , where $j=5, 6, 7$ and 8) of the LMD where the virtual image luminance reaches the same threshold value.
c) For each corner point repeat step 5 while maintaining pointing toward the selected *corner* point. Determine the positions for Δx_{6j} , Δy_{2j} and, Δy_{8j} . Record the (Δx_{ij} , Δy_{ij}) for all positions.
- Optional: Steps 17 and 18 measuring the corner points 1, 3, 7 and, 9 positions.*
17. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
 18. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the corner points, 1, 3, 7 and, 9, in succession, refocusing the LMD on each corner point.
b) For each corner point, translate the LMD to that corner while viewing and measuring the virtual image luminance. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *corner* point. Determine the x-axis position (Δx_{ij}) and y-axis position (Δy_{ij}) (where $i=1, 3, 7$ and, 9 and $j=i$) of the LMD where the virtual image luminance reaches the same threshold value. Return the LMD to the origin following each translation.
c) For each corner point, also translate the LMD to the diagonally opposite corner point while viewing and measuring the virtual image luminance. Use the 2-axis goniometer adjustments to maintain LMD pointing at the original selected corner point. Determine the x-axis position (Δx_{ik}) and y-axis (Δy_{ik}) position (where $i=1, 3, 7$ and, 9 and $k=9, 7, 3$ and, 1) of the LMD where the virtual image luminance reaches the same threshold value. Return the LMD to the origin following each translation.
d) Record the (Δx_{ij} , Δx_{ik} , Δy_{ij} and, Δy_{ik}) for all positions.

19. Calculate the size of the eyebox at the plane of the eye-point as follows:

$$W_{BOX} = \min(\Delta x_{4j}) + \min(\Delta x_{6j}) \quad \text{where } j = 1 \text{ to } 4, 5 \text{ to } 8 \text{ optional}$$

$$H_{BOX} = \min(\Delta y_{2j}) + \min(\Delta y_{8j})$$

20. Calculate the diagonal size of the eyebox at the plane of the eye-point as follows:

$$BD_{BOX} = \sqrt{\left(\min(\Delta x_{1j}, \Delta x_{1k})\right)^2 + \left(\min(\Delta y_{1j}, \Delta y_{1k})\right)^2} + \sqrt{\left(\min(\Delta x_{9j}, \Delta x_{9k})\right)^2 + \left(\min(\Delta y_{9j}, \Delta y_{9k})\right)^2}$$

$$FD_{BOX} = \sqrt{\left(\min(\Delta x_{3j}, \Delta x_{3k})\right)^2 + \left(\min(\Delta y_{3j}, \Delta y_{3k})\right)^2} + \sqrt{\left(\min(\Delta x_{7j}, \Delta x_{7k})\right)^2 + \left(\min(\Delta y_{7j}, \Delta y_{7k})\right)^2}$$

where $j = 1, 3, 7, 9$ and $k = 9, 7, 3, 1$

where Forward Diagonal (FD) is measured from Upper Right (UR) to Lower Left (LL)
and Back Diagonal (BD) is measured from Upper Left (UL) to Lower Right (LR).



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 1. Eyebox Data Example:

Luminance Measurements based on field of view with 50% Threshold

Device Description				NED Device 1				Left Ocular					
Parameter				Measured		Specification		Accept		Reject		Notes	
Eyebox Dimensions by Luminance				Cd/m^2		≥ 50% center							
Eye relief (remember 3 mm Cornea offset)				25 mm		25 mm							
Pupil distance				28 mm		28 mm							
LMD pupil diameter				5 mm		2-5 mm							
Measurement vantage point				Eye rotation		Eye rotation							
Measurement field angle				±1.0 degree		±1.0 degree							
Eye-point alignment				Section 19.3.1									
Virtual Image Focal Distance				1 m		1 diopter							
	Center			Translate Left		Translate Right		Translate Up		Translate Down			
Measurement Location	L (cd/m²)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
1 (θ_1, φ_1)	653	0.0	0.0	-3.8	0.0	4.7	0.0	0.0	3.1	0.0	-4.5		
2 (θ_2, φ_2)	780	0.0	0.0	-4.1	0.0	4.05	0.0	0.0	3.3	0.0	-3.35		
3 (θ_3, φ_3)	650	0.0	0.0	-3.95	0.0	4.0	0.0	0.0	3.2	0.0	-3.3		
4 (θ_4, φ_4)	759	0.0	0.0	-3.95	0.0	4.1	0.0	0.0	3.25	0.0	-3.25		
5 (θ_5, φ_5)	875.0	0.0	0.0										
6 (θ_6, φ_6)	768	0.0	0.0	-4.1	0.0	4.1	0.0	0.0	3.2	0.0	-3.2		
7 (θ_7, φ_7)	641	0.0	0.0	-3.9	0.0	4.5	0.0	0.0	4.2	0.0	-3.2		
8 (θ_8, φ_8)	790	0.0	0.0	-4.05	0.0	4.1	0.0	0.0	3.35	0.0	-3.15		
9 (θ_9, φ_9)	645	0.0	0.0	-4.0	0.0	3.95	0.0	0.0	3.25	0.0	-3.2		
min(Δx) (mm)				3.95									
min(Δy) (mm)										3.2		3.15	
Minimum horizontal eyebox (mm)				8.00									
Minimum vertical eyebox (mm)								6.35					
All cells shaded <div></div> are optional measurements													
Optional Corner Measurements													
	Center			Upper Right		Lower Left		Upper Left		Lower Right			
Measurement Location	L (cd/m²)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
1 (θ_1, φ_1)	653	0.0	0.0					-2.9	2.8	2.9	-3.0		
3 (θ_3, φ_3)	650	0.0	0.0	2.8	2.9	-2.8	-2.75						
7 (θ_7, φ_7)	641	0.0	0.0	2.8	2.9	2.8	-2.75						
9 (θ_9, φ_9)	645	0.0	0.0					-2.85	2.8	2.9	-2.95		
min(Δx) (mm)				2.8		2.8		2.85		2.9			
min(Δy) (mm)						2.9				2.8		2.95	
Mean forward diagonal eyebox (mm)				7.96									
Mean back diagonal eyebox (mm)								8.13					

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 2. Data Example:

Eyebox Widths, Heights and, Diagonals (using recommended method)

Eyebox Dimension (minimum)	Calculated Value	Units	Optionality
W_{BOX}	8.0	mm	Required
H_{BOX}	6.35	mm	Required
FD_{BOX}	7.96	mm	Optional
BD_{BOX}	8.13	mm	Optional

As in section 19.9.1, the above procedure measures the height and width (or, diagonal) of the exit pupil or, the height and width (or, diagonal) of the eyebox at the location of the eye point. The depth range of the eyebox also shall be



determined. To accomplish this, first, the *eyeline* must be established. Generally, it may be assumed that the eyeline is coincident with the optical axis of the NED. However, this may not always be the case. To establish the eyeline, the LMD should be moved away from the eye-point position along the z-axis for some distance. This distance may be a few millimeters. If the image of the full-field white pattern begins to deteriorate around the edges due to vignetting, then the LMD has been moved too far. Slowly move the LMD back toward the eye-point until the edges of the full-field white pattern are just discernable, if, perhaps, a little fuzzy (i.e., slightly out of focus.) Repeat the procedure of section 19.9.1, steps 6 through 11 and 14 or, follow the procedure in Section 19.3, to locate the eye-point. If the new determination of the axial pupil point location relative to the eye-point location remains at $x = y = 0.0$, then the eyeline coincides with the NED optical axis. If the new eye-point is located at $x \neq y \neq 0.0$, then the eyeline is not coincident with the optical axis of the NED. In this case, use the θ and ϕ goniometer adjustments for the NED to align the eyeline to the z-axis of the LMD. .

PROCEDURE, EYEBOX VOLUME:

1. Move the LMD back to the position of the original eye-point.
2. Move the LMD in small steps, perhaps 1mm, away from the original eye-point and repeat the eyebox Cross-Section procedure above, steps 3 – 14 (or, 3-16 or, 3- 18, depending of selected options) and 19 at each step position until reaching the point where the full-field white pattern edges begin to deteriorate as before.
3. Record the results for each step position in a table similar to Table 1, above.
4. Move the LMD back to the original eye-point location and then move the LMD closer to the NED in small steps of the same size used when moving the LMD away from the eye-point.
5. Repeat the eyebox Cross-Section procedure above, steps 3 – 14 (or, 3-16 or, 3- 18, depending of selected options) and 19 for each step position and record the results in tables such as Table 1.
6. Continue this process until a reasonable inside distance has been reached, such as a minimum eye relief distance of 21 mm (+3 mm, corneal thickness.)

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Table 3. Data Example: Eyebox dimension along z-axis					
Device Description	NED Device 1		Left Ocular		
Parameter	Measured	Specification	Accept	Reject	Notes
Eyebox Dimensions by Luminance	Cd/m ²	≥ 50% center			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
LMD pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	±1.0 degree	±1.0 degree			
Eye-point alignment	Section 19.3.1				
Virtual Image Focal Distance	1 m	1 diopter			
Eyeline Position (relative to Eye-point)	Mean Horizontal Eyebox Dimension	Mean Vertical Eyebox Dimension	Mean Forward Diagonal Dimensions	Mean Back Diagonal Dimensions	Units
-4.0 mm	11.71	9.30	11.44	11.90	mm
-3.0 mm	10.65	8.45	10.40	10.82	mm
-2.0 mm	9.68	7.68	9.45	9.84	mm
-1.0 mm	8.80	6.99	8.59	8.94	mm
0.0 mm	8.00	6.35	7.96	8.13	mm
+1.0 mm	7.20	5.72	7.16	7.32	mm
+2.0 mm	6.48	5.14	6.45	6.59	mm
+3.0 mm	5.83	4.63	5.80	5.93	mm
+4.0 mm	5.25	4.17	5.22	5.33	mm

REPORTING: The following items shall be reported:

- Luminance threshold used, LMD entrance pupil position relative to last optical surface, positive and negative x-axis coordinates of eyebox, positive and negative y-axis coordinates of eyebox as shown in Table 1.
- The horizontal and vertical dimensions of the eyebox measured along the eyeline as shown in Table 3.
- Setup details, including LMD and aperture size, eye vantage point and DUT optical axis.

**COMMENTS:**

- (1) **Number of test points:** Generally, this measurement is performed only along the x- and y- axes relative to the optical axis of the NED DUT. This test suite may be performed for several off axis points such as above and below (left and right) of the x- and y-axes to confirm the rectangular shape of the eyebox. However, typically, the shape may be inferred by the NED design and, possibly, also by the rough alignment illustrated in Fig. 2 in section 19.9.1.
- (2) **Test Point Luminance Threshold:** If, when measuring the luminance at any of the edge or corner points, the luminance threshold is not achieved, slowly back off toward the center reference point until the luminance threshold is achieved and use this coordinate to record the measurement.
- (3) **Eye relief:** Not all NED devices offer an eye relief of 25 mm. Generally, the eye relief for any NED ranges from a minimum of 16 mm (common for normal prescription eyewear) to about 28 mm, allowing for the user's own prescription eyewear clearance.
- (4) **Measurement Distance:** If a less than or equal to 28 mm measurement is not achievable for a NED-LMD combination due to size of the aperture mounting or lens size, then it is not possible to use this particular NED-LMD combination.

REFERENCES:

¹ IEC 63145-20-10:2019, "Eyewear Display–Part 20-10: Fundamental measurement methods – Optical properties," International Electrotechnical Commission, 2019.



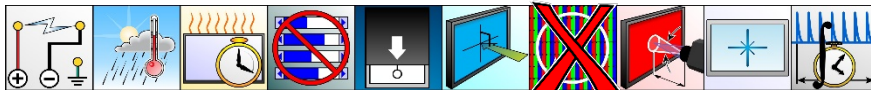
19.9.5 MICHELSON CONTRAST-BASED FIELD OF VIEW METHOD

DESCRIPTION: The methods described in this section and the previous section use the virtual image field of view (FOV) as the reference for measuring the extent of the eyebox. The procedure below resembles the procedure described in section 6.8 of the IEC standard, IEC 63145-20-20-2019¹ while incorporating elements of the procedure described in section 19.8 to measure the angular dimensions of the virtual image FOV. Compared to section 19.9.2 above, this method requires more measurements to obtain the dimensions of the eyebox, but the results may be more applicable as the visible (useable) FOV defines the practical dimensions of the eyebox (see the Terminology section of section 19.0.) If the test setup used to measure the characteristics of the NED or HUD is fully manual, the method of section 19.9.2 may be easier to perform, but likely will overestimate the eyebox compared to the procedure described here.

The Michelson contrast threshold for determination of the eyebox dimensions is an absolute value, $0.0 \leq C_M \leq 1.0$. Typically, the threshold is 0.25 or, 0.50. The measured dimension of the eyebox will depend on the threshold value selected. For the procedure description that follows, a 0.50 threshold is used. However, it is important that the selected threshold value be agreed upon by all stakeholders and that the threshold value is clearly recorded in the test results. Also, note well that virtual image focal distance – the location of the virtual image in image space in front of the viewer – also may affect the determination of the eyebox dimensions. Depending on the design and application for the NED, the virtual image focal distance may be anywhere from approximately 15 inches to infinity, or may cover a similar range if the NED is capable of supporting multiple focal planes as in light-field technology devices. While the virtual image FOV may appear the same over this range, the eyebox measurements may vary – especially if the focal distance is less than about 1 meter. The virtual image focal distance (or, range) shall be reported in the test results.

APPLICATION: This measurement can be used for any near-eye display. These include freeform optics with OLED, LCOS and LED light engines, light-field optics, waveguide optics, holographic optical element (HOE) and retinal writing NEDs.

SETUP: As defined by these icons, standard setup details apply (§ 3.2).



SETUP CONDITIONS FOR FIELD OF VIEW MEASUREMENT

A 2D LMD according to 19.2 shall be used to measure the important characteristics of the NED virtual image. All evaluations are performed within a measurement field angle of ± 1 degree around the optical axis of the LMD. If another measurement field angle is used it shall be reported.

- At least a 5-axis motion apparatus is needed to scan over a range of viewing directions and translations. This can be achieved by holding the NED or HUD fixed and moving the LMD, or by keeping the LMD fixed and moving the NED or HUD. It is often convenient to have some alignment capability in both the device under test (DUT) and the LMD. The setup using an array-type LMD and, as an example, an AR-type NED is shown in Fig. 1 of section 19.9.2 above.
- The eye center rotation vantage point method (19.5) generally is used to scan over the virtual image field of view. The LMD entrance pupil is placed at the eye-point and the LMD is pivoted about a position 10 mm behind the entrance pupil.
- The measurement distance between the NED or HUD and the LMD should be specified by the manufacturer. However, this is often not defined. If the eye relief is not specified for an NED, it shall be assumed to be 25 mm (from the center of the last NED optical element to the vertex of the cornea). Using the standard eye model in 19.1, the entrance pupil should be placed 3 mm behind the vertex of the cornea, or 28 mm from the last NED optic.
- When using a 2D LMD, the LMD should have a photopic response, a ± 1.0 degree diameter region of interest (measurement area), and it is useful to have a FOV that is larger than the virtual image. The 2D LMD should have background, flat field, and geometric corrections applied.
- The test pattern for this measurement is a Michelson contrast grille pattern with vertical or horizontal 1-pixel lines alternating on-off as illustrated in Fig. 2 in section 19.9.2. If a > 0.50 Michelson contrast cannot be achieved in the virtual image center with this grille pattern, then a lower spatial frequency pattern should be used. An alignment pattern that may be used is illustrated in Fig. 1 in section 19.9.4 above. This pattern is similar to the one used in section 19.8 to measure the virtual image FOV. In the five position measurement case, the center point is number 5 and the corner points are 1, 3, 7, and 9, from upper left to bottom right. A 25-point alignment pattern also may be used as shown in Section 19.8, Fig. 1.
- A rough visual alignment of the LMD can be made by placing the LMD entrance pupil at the approximate center of the light field projected behind the NED, see Fig. 2 of section 19.9.1.
- A goniometric motion apparatus is needed to scan over a range of viewing directions using the reference eye center rotation vantage point method.
- The difference between the Michelson contrast measured at the center of the virtual image and the threshold value selected will affect the measured size of the eyebox. If the center reference Michelson contrast is only slightly higher than 0.5 and the threshold value selected is 0.5, the measured eyebox will be quite small. While a Michelson contrast near 1.0 typically is not achievable, a value > 0.8 is preferred. If the center reference Michelson contrast is near 0.5, a lower



threshold value, perhaps 0.25, should be selected. Decreasing the spatial frequency of the grille test patterns also should increase the center reference Michelson contrast measured.

This test method *requires* prior measurement of the angular dimensions of the virtual image FOV as described in section 19.8 as some or, all of the FOV points will be needed in the following procedure.

PROCEDURE, EYEBOX CROSS-SECTION:

The following procedure is recommended for this measurement.

1. a) Place the entrance pupil of the LMD at the measurement distance specified by the manufacturer for the NED to be measured. If no measurement distance is specified, place the entrance pupil of the LMD 28 mm from the last optic of the NED, along its optic axis (z-axis) or eyeline.
b) Laterally position the LMD entrance pupil approximately in the center of the light field projected behind the NED (see 19.3 and Fig. 2 in section 19.9.1).
c) Render an alignment target (such as a crosshair) at the virtual image to identify the center of the image. Focus the LMD on the virtual image target.
d) Use the eye center rotation vantage point method (19.5) to rotate the LMD field of view to the center of the virtual image.
2. Using the measured FOV points from the prior FOV test, as described in section 19.8, determine the 9 points (in this example but, may be 5 or 25 also) by calculating the angular field positions (θ, ϕ in degrees) 10% inside (toward the FOV center) the FOV measurements points. These are the new 9 measurement points for this test method as indicated by the inward pointing arrows in Fig. 2 in section 19.9.4.
3. a) Using the θ and ϕ goniometer adjustments direct the pointing of the LMD to point 5.
b) Present the vertical grille test pattern with the selected spatial frequency for the eyebox measurement— such as the vertical 1-pixel on-offline pattern in Fig. 2 in section 19.9.2 or, Fig. 1 in section 19.4.2.
c) This is the center reference Michelson contrast for this evaluation. Capture an image of the test pattern with LMD near the center of the eyebox location. Using the capture tools, measure the Michelson contrast along 3 or more horizontal lines near the center of the captured image:

$$C_{M_v} = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}, \text{ where}$$

$\overline{L_W}$ is the ensemble average of the light (white) measurements and $\overline{L_K}$ is the ensemble average of the dark (black) measurements.

- d) Switch to the horizontal line version of this pattern. The desired threshold requirement should be the same for both the vertical and horizontal grille patterns.
 - e) Using the capture tools, measure the Michelson contrast along 3 or more vertical lines near the center of the captured image:
- $$C_{M_h} = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}$$
4. a) Return to the vertical grille pattern.
b) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the left-side point 4. Refocus the LMD on this point.
c) Laterally translate the LMD to the left. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the negative x-axis position (Δx_{41}) of the LMD where the virtual image Michelson contrast, C_{M_v} , reaches the desired threshold value (for example, 0.25 or 0.50.) The virtual image pattern will begin to fade at one edge as illustrated in Fig. 3a in section 19.9.2.
 5. a) Laterally translate the LMD to the right. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the positive x-axis position (Δx_{61}) of the LMD where the virtual image Michelson contrast reaches the same desired threshold value.
b) Translate the LMD back to the origin and then translate it up toward point 2. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the positive y-axis position (Δy_{21}) of the LMD where the virtual image Michelson contrast reaches the same desired threshold value.
c) Translate the LMD down toward point 8. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *left-side* point. Determine the negative y-axis position (Δy_{81}) of the LMD where the virtual image Michelson contrast reaches the same desired threshold value.
d) Record the ($\Delta x_{i1}, \Delta y_{i1}$) for all positions.
 6. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Switch to the horizontal line version of this pattern to measure the Michelson contrast, C_{M_h} .
c) Repeat steps 4b) and c) and step 5.



7. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Return to the vertical grille pattern.
c) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the right-side point 6. Refocus the LMD on this point.
d) Laterally translate the LMD to the left. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *right*-side point. Determine the negative x-axis position (Δx_{42}) of the LMD where the virtual image Michelson contrast, C_{Mv} , reaches the same threshold value (e.g., 0.50).
e) Repeat step 5 while maintaining pointing toward the right-side point 6. Determine the positions for Δx_{62} , Δy_{22} and, Δy_{82} . Record the (Δx_{i2} , Δy_{i2}) for all positions.
 8. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Switch to the horizontal line version of this pattern to measure the Michelson contrast, C_{Mh} .
c) Repeat steps 7c) through e).
 9. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Return to the vertical grille pattern.
c) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the *top*-side point 2. Refocus the LMD on this point.
d) Laterally translate the LMD to the left. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *top*-side point. Determine the negative x-axis position (Δx_{43}) of the LMD where the virtual image Michelson contrast reaches the same threshold value.
e) Repeat step 5 while maintaining pointing toward the *top*-side point 2. Determine the positions for Δx_{63} , Δy_{23} and, Δy_{83} . Record the (Δx_{i3} , Δy_{i3}) for all positions.
 10. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Switch to the horizontal line version of this pattern to measure the Michelson contrast, C_{Mh} .
c) Repeat steps 9c) through e).
 11. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Return to the vertical grille pattern.
c) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the *bottom*-side point 8. Refocus the LMD on this point.
d) Laterally translate the LMD to the left. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *bottom*-side point. Determine the negative x-axis position (Δx_{44}) of the LMD where the virtual image Michelson contrast reaches the same threshold value.
e) Repeat step 5 while maintaining pointing toward the *bottom*-side point 8. Determine the positions for Δx_{64} , Δy_{24} and, Δy_{84} . Record the (Δx_{i4} , Δy_{i4}) for all positions.
 12. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Switch to the horizontal line version of this pattern to measure the Michelson contrast, C_{Mh} .
c) Repeat steps 11c) through e).
- Optional: Steps 13 through 15 using the corner points 1, 3, 7 and, 9 as reference points.*
13. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
14. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the corner points, 1, 3, 7 and, 9, in succession, refocusing the LMD on each corner point.
b) For each corner point, laterally translate the LMD to the left while viewing and measuring the virtual image Michelson contrast. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *corner* point. Determine the x-axis position (Δx_{4j} , where $j=5, 6, 7$ and 8) of the LMD where the virtual image Michelson contrast reaches the same threshold value.
c) For each corner point repeat step 5 while maintaining pointing toward the selected *corner* point. Determine the positions for Δx_{6j} , Δy_{2j} and, Δy_{8j} . Record the (Δx_{ij} , Δy_{ij}) for all positions.
15. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
b) Switch to the horizontal line version of this pattern to measure the Michelson contrast, C_{Mh} .
c) Repeat step 14.



Optional: Steps 16 through 18 measuring the corner points 1, 3, 7 and, 9 positions.

16. Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
17. a) Using the θ and ϕ goniometer adjustments direct the LMD pointing to the corner points, 1, 3, 7 and, 9, in succession, refocusing the LMD on each corner point.
 b) For each corner point, translate the LMD to that corner while viewing and measuring the virtual image Michelson contrast. Use the 2-axis goniometer adjustments to maintain LMD pointing at the selected *corner* point. Determine the x-axis position (Δx_{ij}) and y-axis position (Δy_{ij}) (where $i=1, 3, 7$ and, 9 and $j=i$) of the LMD where the virtual image Michelson contrast reaches the same threshold value. Return the LMD to the origin following each translation.
 c) For each corner point, also translate the LMD to the diagonally opposite corner point while viewing and measuring the virtual image Michelson contrast. Use the 2-axis goniometer adjustments to maintain LMD pointing at the original selected *corner* point. Determine the x-axis position (Δx_{ik}) and y-axis (Δy_{ik}) position (where $i=1, 3, 7$ and, 9 and $k=9, 7, 3$ and, 1) of the LMD where the virtual image Michelson contrast reaches the same threshold value. Return the LMD to the origin following each translation.
 d) Record the (Δx_{ij} , Δx_{ik} , Δy_{ij} and, Δy_{ik}) for all positions.
18. a) Return the LMD to the center (origin) position. Repeat steps 1.c) and d) above if necessary and reset position to $x=0$. Employ backlash compensation steps if required.
 b) Switch to the horizontal line version of this pattern to measure the Michelson contrast, C_{Mh} .
 c) Repeat step 17.
19. Calculate the size of the eyebox at the plane of the eye-point as follows:

$$W_{BOX} = \min(\Delta x_{4j}) + \min(\Delta x_{6j}) \quad \text{where } j = 1 \text{ to } 4, 5 \text{ to } 8 \text{ optional}$$

$$H_{BOX} = \min(\Delta y_{2j}) + \min(\Delta y_{8j})$$

The $\min(\Delta x_{ij})$ and $\min(\Delta y_{ij})$ include the Michelson contrast measurements for both the vertical and the horizontal grille patterns, C_{Mv} and C_{Mh} .

20. Calculate the diagonal size of the eyebox at the plane of the eye-point as follows:

$$BD_{BOX} = \sqrt{(\min(\Delta x_{1j}, \Delta x_{1k}))^2 + (\min(\Delta y_{1j}, \Delta y_{1k}))^2} + \sqrt{(\min(\Delta x_{9j}, \Delta x_{9k}))^2 + (\min(\Delta y_{9j}, \Delta y_{9k}))^2}$$

$$FD_{BOX} = \sqrt{(\min(\Delta x_{3j}, \Delta x_{3k}))^2 + (\min(\Delta y_{3j}, \Delta y_{3k}))^2} + \sqrt{(\min(\Delta x_{7j}, \Delta x_{7k}))^2 + (\min(\Delta y_{7j}, \Delta y_{7k}))^2}$$

where $j = 1, 3, 7, 9$ and $k = 9, 7, 3, 1$

where Forward Diagonal (FD) is measured from Upper Right (UR) to Lower Left (LL)
 and Back Diagonal (BD) is measured from Upper Left (UL) to Lower Right (LR).

The $\min(\Delta x_{ij})$ and $\min(\Delta y_{ij})$ include the Michelson contrast measurements for both the vertical and the horizontal grille patterns, C_{Mv} and C_{Mh} .

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 1. Eyebox data example:

Michelson contrast measurements based on field of view with 50% Threshold

Device Description	NED Device 1		Left Ocular		
	Measured	Specification	Accept	Reject	Notes
Michelson contrast center reference value	0.85	>0.80			
Michelson contrast edge threshold		≥ 0.50			
Grille pattern spatial frequency	1-pixel	1-pixel			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
LMD pupil diameter	5 mm	2-5 mm			
Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	± 1.0 degree	± 1.0 degree			
Eye-point alignment	Section 19.3.1				
Virtual Image Focal Distance	1 m	1 diopter			



Table 1. Continued

Vertical Grille	Center			Translate Left		Translate Right		Translate Up		Translate Down	
Measurement Location	C_{MV}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
1 (θ_1, φ_1)	653	0.0	0.0	-3.8	0.0	4.7	0.0	0.0	3.1	0.0	-4.5
2 (θ_2, φ_2)	780	0.0	0.0	-4.1	0.0	4.05	0.0	0.0	3.3	0.0	-3.35
3 (θ_3, φ_3)	650	0.0	0.0	-3.95	0.0	4.0	0.0	0.0	3.2	0.0	-3.3
4 (θ_4, φ_4)	759	0.0	0.0	-3.95	0.0	4.1	0.0	0.0	3.25	0.0	-3.25
5 (θ_5, φ_5)	875.0	0.0	0.0								
6 (θ_6, φ_6)	768	0.0	0.0	-4.1	0.0	4.1	0.0	0.0	3.2	0.0	-3.2
7 (θ_7, φ_7)	641	0.0	0.0	-3.9	0.0	4.5	0.0	0.0	4.2	0.0	-3.2
8 (θ_8, φ_8)	790	0.0	0.0	-4.05	0.0	4.1	0.0	0.0	3.35	0.0	-3.15
9 (θ_9, φ_9)	645	0.0	0.0	-4.0	0.0	3.95	0.0	0.0	3.25	0.0	-3.2
min(Δ x) (mm)				3.95		4.05					
min(Δ y) (mm)									3.2		3.15
Minimum horizontal eyebox (mm)				8.00							
Minimum vertical eyebox (mm)								6.35			
Horiz. Grille	Center			Translate Left		Translate Right		Translate Up		Translate Down	
Measurement Location	C_{MH}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
1 (θ_1, φ_1)	653	0.0	0.0	-3.9	0.0	4.6	0.0	0.0	3.3	0.0	-4.3
2 (θ_2, φ_2)	780	0.0	0.0	-4.2	0.0	4.15	0.0	0.0	3.23	0.0	-3.31
3 (θ_3, φ_3)	650	0.0	0.0	-3.85	0.0	4.1	0.0	0.0	3.0	0.0	-3.45
4 (θ_4, φ_4)	759	0.0	0.0	-3.75	0.0	4.0	0.0	0.0	3.2	0.0	-3.15
5 (θ_5, φ_5)	875.0	0.0	0.0								
6 (θ_6, φ_6)	768	0.0	0.0	-4.2	0.0	4.1	0.0	0.0	3.3	0.0	-3.1
7 (θ_7, φ_7)	641	0.0	0.0	-3.8	0.0	4.4	0.0	0.0	4.2	0.0	-3.4
8 (θ_8, φ_8)	790	0.0	0.0	-4.25	0.0	4.3	0.0	0.0	3.25	0.0	-3.2
9 (θ_9, φ_9)	645	0.0	0.0	-4.1	0.0	3.85	0.0	0.0	3.15	0.0	-3.25
min(Δ x) (mm)				3.75		4.0					
min(Δ y) (mm)									3.0		3.1
Minimum horizontal eyebox (mm)				7.75							
Minimum vertical eyebox (mm)								6.1			
All cells shaded <div></div> are optional measurements											
Optional Corner Measurements											
Vertical Grille	Center			Upper Right		Lower Left		Upper Left		Lower Right	
Measurement Location	C_{MV}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
1 (θ_1, φ_1)	653	0.0	0.0					-2.9	2.8	2.9	-3.0
3 (θ_3, φ_3)	650	0.0	0.0	2.8	2.9	-2.8	-2.75				
7 (θ_7, φ_7)	641	0.0	0.0	2.8	2.9	2.8	-2.75				
9 (θ_9, φ_9)	645	0.0	0.0					-2.85	2.8	2.9	-2.95
min(Δ x) (mm)				2.8		2.8		2.85		2.9	
min(Δ y) (mm)					2.9		2.75		2.8		2.95
Mean forward diagonal eyebox (mm)				7.96							
Mean back diagonal eyebox (mm)								8.13			
Horiz. Grille	Center			Upper Right		Lower Left		Upper Left		Lower Right	
Measurement Location	C_{MH}	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)	x (mm)	y (mm)
1 (θ_1, φ_1)	653	0.0	0.0					-3.0	2.9	3.1	-3.0
3 (θ_3, φ_3)	650	0.0	0.0	3.2	3.1	-3.1	-2.9				
7 (θ_7, φ_7)	641	0.0	0.0	3.0	3.1	3.1	-2.85				
9 (θ_9, φ_9)	645	0.0	0.0					-3.15	2.8	3.1	-3.0
min(Δ x) (mm)				3.0		3.1		3.0		3.1	
min(Δ y) (mm)					3.1		2.85		2.8		3.0
Mean forward diagonal eyebox (mm)				8.52							
Mean back diagonal eyebox (mm)								8.42			



—SAMPLE DATA ONLY—			
Do not use any values shown to represent expected results of your measurements.			
Table 2. Data Example: Eyebbox Widths, Heights and, Diagonals (using recommended method)			
Eyebbox Dimension (minimum)	Calculated Value	Units	Optionality
W_{BOX}	7.75	mm	Required
H_{BOX}	6.10	mm	Required
FD_{BOX}	7.96	mm	Optional
BD_{BOX}	8.13	mm	Optional

As in section 19.9.2, the above procedure measures the height and width (or, diagonal) of the exit pupil or, the height and width (or, diagonal) of the eyebbox at the location of the eye point. The depth range of the eyebbox also shall be determined. To accomplish this, first, the *eyeline* must be established. Generally, it may be assumed that the eyeline is coincident with the optical axis of the NED. However, this may not always be the case. To establish the eyeline, the LMD should be moved away from the eye-point position along the z-axis for some distance. This distance may be a few millimeters. If the image of the full-field white pattern begins to deteriorate around the edges due to vignetting, then the LMD has been moved too far. Slowly move the LMD back toward the eye-point until the edges of the grille pattern are just discernable, if, perhaps, a little fuzzy (i.e., slightly out of focus.) Repeat the procedure of section 19.9.2, steps 8 through 15 and 18 or, follow the procedure in Section 19.3, to locate the eye-point. If the new determination of the axial pupil point location relative to the eye-point location remains at $x = y = 0.0$, then the eyeline coincides with the NED optical axis. If the new eye-point is located at $x \neq y \neq 0.0$, then the eyeline is not coincident with the optical axis of the NED. In this case, use the θ and ϕ goniometer adjustments for the NED to align the eyeline to the z-axis of the LMD.

PROCEDURE, EYEBBOX VOLUME:

1. Move the LMD back to the position of the original eye-point.
2. Move the LMD in small steps, perhaps 1 mm, away from the original eye-point and repeat the eyebbox Cross-Section procedure above, steps 3 – 12 (or, 3-15 or, 3- 18, depending of selected options) at each step position until reaching the point where the grille pattern edges begin to deteriorate as before.
3. Record the results for each step position in a table similar to Table 1, above.
4. Move the LMD back to the original eye-point location and then move the LMD closer to the NED in small steps of the same size used when moving the LMD away from the eye-point.
5. Repeat the recommended procedure above, steps 3 –12 (or, 3-15 or, 3- 18, depending on selected options) for each step position and record the results in tables such as Table 1.
6. Continue this process until a reasonable inside distance has been reached, such as a minimum eye relief distance of 21 mm (+3 mm, corneal thickness.)
7. *Optional corner point measurement:* Repeat the above procedure steps 2 – 6 for the corner points: UL, UR, LL and, LR.
8. Use the results to calculate the mean eyebbox height, width, forward and back diagonals from the mean vertical and horizontal grille results as shown in Table 2.

—SAMPLE DATA ONLY—					
Do not use any values shown to represent expected results of your measurements.					
Table 3. Data Example: Eyebbox dimension along z-axis					
Device Description	NED Device 1		Left Ocular		
Parameter	Measured	Specification	Accept	Reject	Notes
Michelson contrast center reference value	0.85	>0.80			
Michelson contrast edge threshold		> 0.50			
Grille pattern spatial frequency	1-pixel	1-pixel			
Eye relief (remember 3 mm Cornea offset)	25 mm	25 mm			
Pupil distance	28 mm	28 mm			
LMD pupil diameter	5 mm	2-5 mm			



Measurement vantage point	Eye rotation	Eye rotation			
Measurement field angle	±1.0 degree	±1.0 degree			
Eye-point alignment	Section 19.3.1				
Virtual Image Focal Distance	1 m	1 diopter			

Table 3. Continued

Eyeline Position (relative to Eye-point)	Mean Horizontal Eyebbox Dimension	Mean Vertical Eyebbox Dimension	Mean Forward Diagonal Dimensions	Mean Back Diagonal Dimensions	Units
-4.0 mm	11.35	8.93	11.65	11.90	mm
-3.0 mm	10.32	8.12	10.59	10.82	mm
-2.0 mm	9.38	7.38	9.63	9.84	mm
-1.0 mm	8.53	6.71	8.76	8.94	mm
0.0 mm	7.75	6.10	7.96	8.13	mm
+1.0 mm	6.98	5.49	7.16	7.32	mm
+2.0 mm	6.28	4.94	6.45	6.59	mm
+3.0 mm	5.65	4.45	5.80	5.93	mm
+4.0 mm	5.08	4.00	5.22	5.33	mm

REPORTING: The following items shall be reported:

- Michelson contrast threshold used, LMD entrance pupil position relative to last optical surface, positive and negative x-axis coordinates of eyebbox, positive and negative y-axis coordinates of eyebbox as shown in Table 1;
- The horizontal and vertical dimensions of the eyebbox measured along the eyeline as shown in Table 3.
- Setup details, including LMD and aperture size, eye vantage point and DUT optical axis.
- Grille pattern spatial frequency.

COMMENTS:

- (1) **Number of test points:** Generally, this measurement is performed only along the x- and y- axes relative to the optical axis of the NED DUT. This test suite may be performed for several off axis points such as above and below (left and right) of the x- and y-axes to confirm the rectangular shape of the eyebbox. However, typically, the shape may be inferred by the NED design and, possibly, also by the rough alignment illustrated in Fig. 2 in section 19.9.1.
- (2) **Test Point Contrast Threshold:** If, when measuring the Michelson contrast at any of the edge or corner points, the threshold is not achieved, slowly back off toward the center reference point until the contrast threshold is achieved and use this coordinate to record the measurement.
- (2) **Eye relief:** Not all NED devices offer an eye relief of 25 mm. Generally, the eye relief for any NED ranges from a minimum of 16 mm (common for normal prescription eyewear) to about 28 mm, allowing for the user's own prescription eyewear clearance.
- (3) **Measurement distance:** If a less than or equal to 28 mm measurement is not achievable for a NED-LMD combination due to size of the aperture mounting or lens size, then it is not possible to use this particular NED-LMD combination.

REFERENCES:

- ¹ IEC 63145-20-20:2019, "Eyewear Display—Part 20-20: Fundamental measurement methods – Image Quality," International Electrotechnical Commission, 2020.



19.10 TRANSMITTANCE OF AR DUTs

ALIAS: Ambient Visibility, Ambient Throughput.

DESCRIPTION: Augmented Reality (AR) displays are unique among near-eye displays in that they optically combine the computer-generated (CG) information with the physical world (ambient scene) surrounding the user. For the seamless overlay of CG on the ambient scene, the luminance of the two image fields must be balanced over a range of ambient conditions such that the CG information is readable and useable.

There are many methods used in various NEDs to combine the Ambient and CG information. Frequently used designs include the following:

- Tilted half-tone mirror
- Single large curved reflector
- Bird-bath combiner
- See-around prism combiner
- Off-axis curved Reflector
- Free-form total internal reflection (TIR) prism
- Waveguide combiner
- Laser-scanning holographic combiner

Figure 1 illustrates the tilted half-tone mirror combiner¹ type. A partially reflecting (generally 50%) mirror is located in front of the user's eye. The CG information is provided by the imager device and the imaging optics relays the information to the user's eye reflecting from the partial mirror, forming a virtual image in front of the user. The user views the ambient scene directly through the partial mirror that reflects 50% of the ambient luminance away from the user's eye. The visor/cover is a clear plastic window providing some mechanical protection of the optical elements. The visor/cover also provides a stand-off for the optical elements when setting the display on a flat, hard surface.

Figs. 2, 3, 4 and, 5 illustrate four of the most common combiner forms¹: the two-partial-reflector Bird-Bath combiner, the free-form TIR prism combiner, an example diffractive-coupled "waveguide" combiner[†] and, the laser-scanning holographic combiner. The bird-bath combiner shown in Fig. 2 reflects the CG information away from the user's eye and adds a curved partial mirror to form the image for the user. This configuration provides superior image quality to that of the single tilted mirror in Fig. 1. This design also provides more flexibility for the optical design and the magnification range – eye box size. However, the ambient and CG luminance are reduced from 2 to 1 compared to the Fig. 1 configuration since the bird-bath

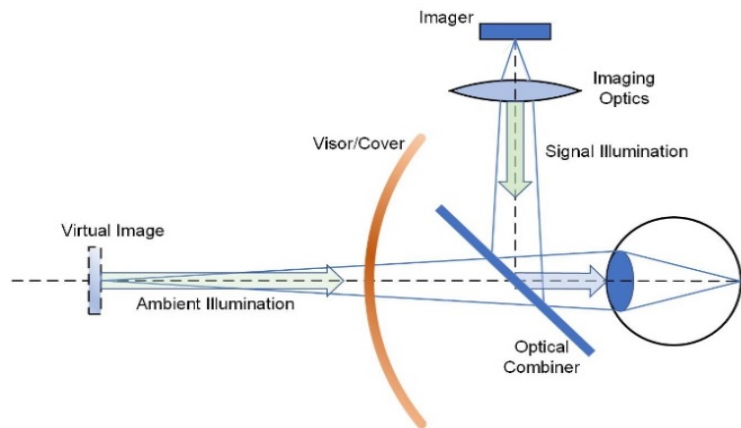


Fig. 1. Tilted half-tone ($R=50\%$) mirror combiner.

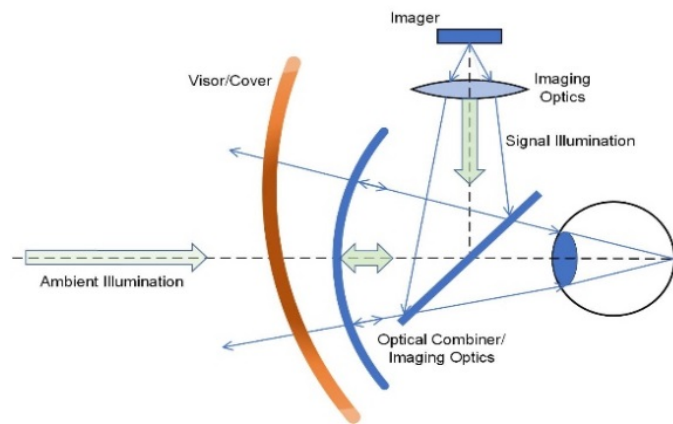


Fig. 2. Bird-bath combiner.

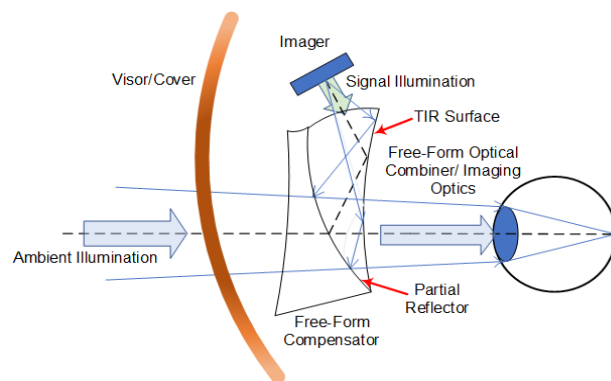


Fig. 3. Free-form TIR prism combiner.

[†] Strictly, these are light guides, not waveguides since light propagates by total internal reflection as long as the surface-incidence angle remains greater than the critical angle. No propagation modes form within the guide medium.



combiner implements two partial (typically, 50%) reflectors.

In Fig. 3, the free-form TIR prism configuration^{2,3} replaces the two partial mirrors of Fig. 2 with a single partial mirror and a TIR mirror. The CG information signal refracts through the first prism surface such that it impinges the second surface at greater than the critical angle for total internal reflection (no partial metal reflector needed). The CG signal then reflects from the third prism surface – with a partial reflector – back through the prism, transmitting to the user's eye since incidence at the second surface now is less than the critical angle for TIR. The compensator prism plays no role in the CG information imaging for the user – it corrects for the distortion of the ambient scene introduced by the TIR prism. The transmission loss due to partial reflectors is reduced back to a maximum of 50% while providing a much more compact implementation of the optical combiner.

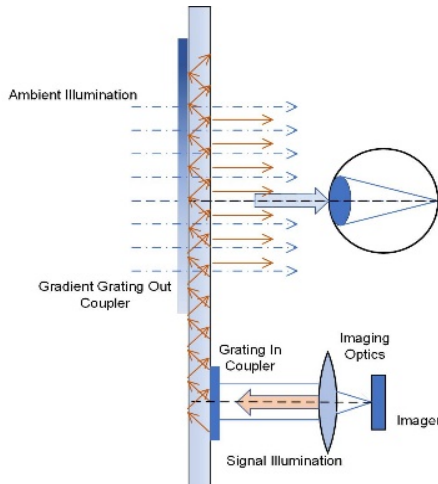


Fig. 4. Waveguide combiner

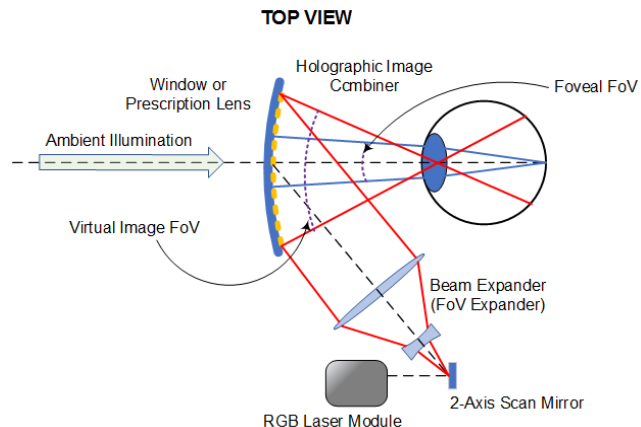


Fig. 5. Laser-scanning holographic combiner

Figure 4 illustrates one of the more recent forms of the AR optical combiners – the diffractive waveguide combiner. A diffraction grating – either surface-relief or holographic – couples the CG signal illumination into the light guide (waveguide) through which the light propagates by TIR until the wavefront aligns with part of the gradient out-coupling grating located in front of the user's eye. The out-grating is large, covering much of the user's field of view, providing a large eye box for the user. Since there are no partial reflector surfaces, the ambient transmission typically is very high – on the order of 90%. However, while the ambient transmission is high, the signal throughput is very low, typically not exceeding 10% – primarily due to coupling losses. This implies that a typical office lighting environment (luminance is approximately 150 cd/m²) may significantly wash out the CG signal. Consequently, many waveguide combiners reduce the ambient transmission through either tinting or, partial reflection, to perhaps 30% to better balance with the low CG signal illumination.

Figure 5 illustrates the laser-scanning (aka retinal-scanning) holographic image combiner. Early versions of laser-scanning image formation utilized free-space image combiners such as those illustrated in Figs 1 and 2. More recently, however, the holographic image combiner⁴ is implemented to redirect the CG information toward the user's eyes using a 1st-order reflective holographic diffraction grating. The Holographic element can be located on a glass or plastic window or, on a prescription spectacle lens for custom prescription eyewear. The laser-scanning approach for image formation has the advantage of a very large depth of focus – making it quite ideal for 3D applications. CG images may be located at various field positions using visual cues such as convergence, binocular disparity, occlusion and, shading without the need for multiple imaging planes. However, the laser-scanning technique also suffers from a typically very small imaging system exit pupil – much smaller than the nominal human eye pupil size. Several methods have been used to provide a more typical eyebox size. These include diffractive pupil multipliers – generating an array of exit pupils to increase the effective eyebox size; adding a fast-steering mirror (FSM) in the optical path to dither the image information at the holographic combiner to spread the diffracted image and expand the eyebox, and; adding small phase variations to the holographic grating structure to increase the 1st-order fan-out producing a larger eyebox size.

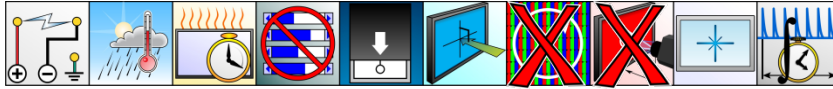
When making luminance measurements on various types of near-eye display devices, care should be taken to prevent scattered, diffracted or, otherwise stray illumination from affecting the measurement. For the basic free-space combiner configurations shown in Figs. 1 and 2, there is little concern. For the case of the free-form prism configuration illustrated in Fig. 3, the presence or, absence of an anti-reflective (AR) coating on the TIR surface of the prism should be known. An AR coating affects the TIR condition such that the critical angle will be different with the coating. The prism design can be such that either situation is accommodated. However, during luminance measurements the absence of an AR coating on the TIR surface may produce undesired Fresnel reflections within the NED optics that may scatter stray illumination into the LMD measurement field angle. Also, for the waveguide and laser scanning configurations depicted in Figs. 4 and 5, the waveguides and holographic (diffractive) elements used to direct the CG image may scatter ambient illumination in unwanted directions within the NED and/or the LMD optical systems. For these configurations, in particular,



pre-evaluation of the transmissive characteristics of the holographic/diffractive elements is advised. Procedures for transmittance factor evaluation of optical elements are included in Sections 11.13 and 11.14 of this standard. As noted in Section 11.13, the measurement can be strongly affected by the scatter properties of the optical elements, especially if nontrivial matrix scatter or haze is present. The procedures described in Section 11.13 are similar to ones described in other optical standards^{5,6}. For most modern optical polymer materials, however, the haze factor is very small, less than 1%.

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic near-eye displays that use free-space, waveguide-type or, laser-scanning holographic ambient illumination optical combiners.

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



OTHER SETUP CONDITIONS: (1) **Number of Pixels Measured:** Typically, in practice, measurements with fewer than 500 pixels are sufficient to achieve adequate reproducibility of the measurements. (2) **Measurement Field Angle:** The measurement field angle must be less than or equal to 2° so that the lens of the LMD better simulates the size of the eye. (3) **Alignment Pattern:** Use an appropriate test pattern to locate the center of the eyebox.

The basic setup is shown in Fig. 6. The illumination source and the LMD are aligned coaxially. The illumination source should be diffuse while the LMD should be directional. The illumination source should be a spectrally smooth bandwidth light source over the visual spectral range. The illumination source should be an integrating sphere with High-Brightness White LED elements feeding the input port as shown in Fig. 6. The spectra of White LEDs can vary

quite substantially. LEDs should be selected that exhibit a CCT near the 6500K illuminator standard. Similarly, the LED source elements may be a mixture of Warm (3500K) and Cool (7000K) LEDs to better match the D65 illumination standard. An exact match is not necessary as the Analysis section provides a mathematical adjustment for color temperature.

The directional LMD imitates a human eye. See Section 3.7 and Section 19.2 for details and nomenclature for the LMD. The DUT is located between the illumination source and the LMD with the integrating sphere exit port as close as possible to the outer most optical element. The LMD should be located 28 mm from the center of the last optical element in the DUT to the field stop of the LMD. This corresponds to an eye relief distance of 25 mm plus the internal location of the field stop in the LMD. The DUT should be aligned along the common optical axis with the illumination source and the LMD such that the entrance pupil of the LMD collocates with the eyebox. See Section 19.3 for procedures used to locate the center of the eyebox. Once the positions and alignments for the illumination source and the LMD are set, they should not be moved until the test is complete.

The Near Eye Display DUT should be mounted such that, once aligned with the illumination source and the LMD it should not be moved until the last step in the procedure. The LMD should be focused at the same focal distance as the DUT virtual image.

It should be noted that in all cases the setup should prevent illuminating the NED beyond the FOV of the virtual image or, the mechanical limits of the combiner optical elements. This can lead to stray illumination captured by the LMD optical system or, reflected from other NED optical elements that can produce veiling glare affecting the luminance measurements.

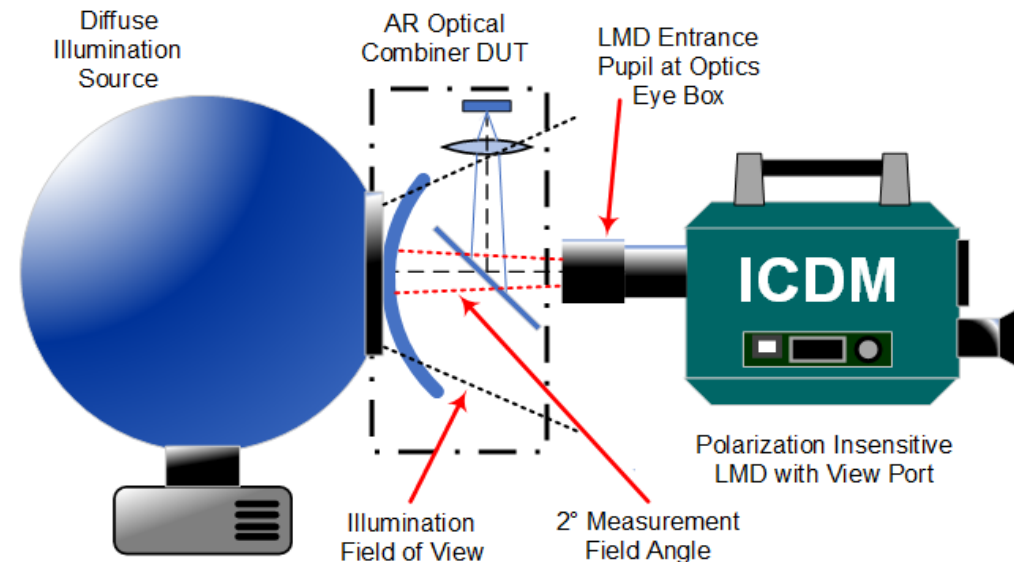


Fig. 6. Ambient Transmittance Test Configuration.



The setup illustrated in Fig. 6 is intended for on-axis ambient luminance measurements only or, for multi-point measurements near the center of the NED virtual image field of view (FOV). This setup may be used for multi-point measurements over the full virtual image FOV if a large integrating sphere – one with an exit port of sufficient diameter to meet or exceed the projected diagonal dimension of the NED's specified FOV. Since large integrating spheres are expensive and one may not be available, the setup illustrated in Fig. 7 may be an acceptable alternative.

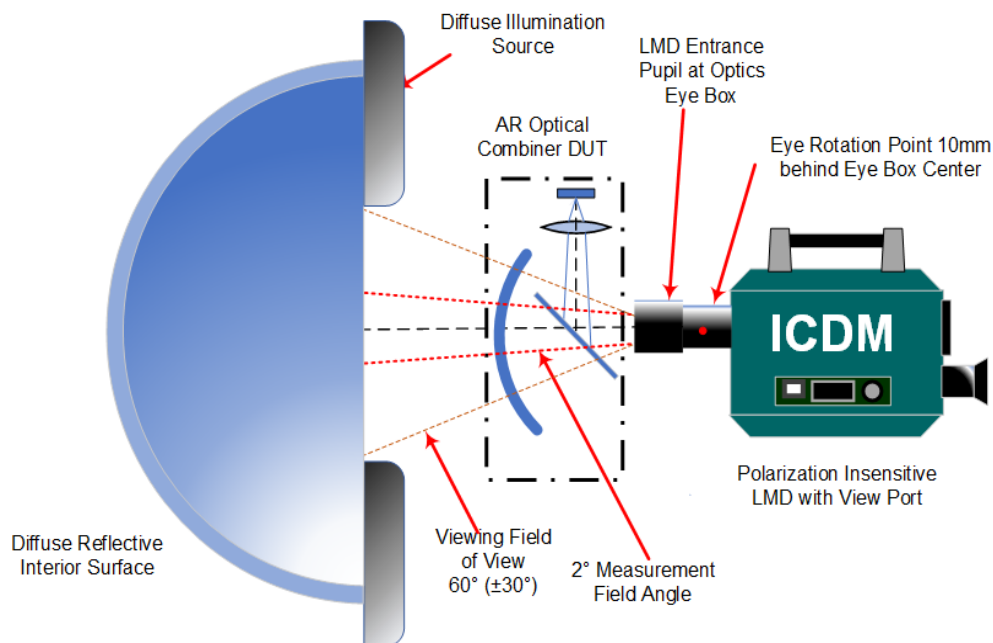


Fig. 7. Alternate Ambient Transmittance Test Configuration.

The device depicted in Fig. 7 is a hemispheric shell internally coated with a diffuse reflecting material – much like a typical integrating sphere. A diffuse illumination source such as a ring illuminator is mounted to the open side of the shell thus, illuminating the shell interior. As depicted in Fig. 7, the center opening is 75 mm in diameter and is uniformly illuminated approximately 97% across the full area of the central opening. Figure 7 shows the hemispheric illuminator spaced in front of the NED DUT such that a diagonal FOV of $60^\circ (\pm 30^\circ)$ is accommodated. With this setup, multi-point measurements may be made of 5, 9 or, 25 points across the virtual image FOV. Figure 8 illustrates the 5-point measurements for the NED DUT ambient illumination. (Refer to section 19.5)

The above alignment of the DUT to the LMD represents the eye pupil vantage point as described in Section 19.1. The alternative center of rotation is the eye rotation vantage point that assumes eye rotation about the eye center of rotation. To adjust the setup shown in either Fig. 6 or, Fig. 7 for eye rotation vantage point measurements, rather than aligning the goniometer center of rotation (both Θ_x and Θ_y) with the entrance pupil of the LMD, the LMD should be mounted such that

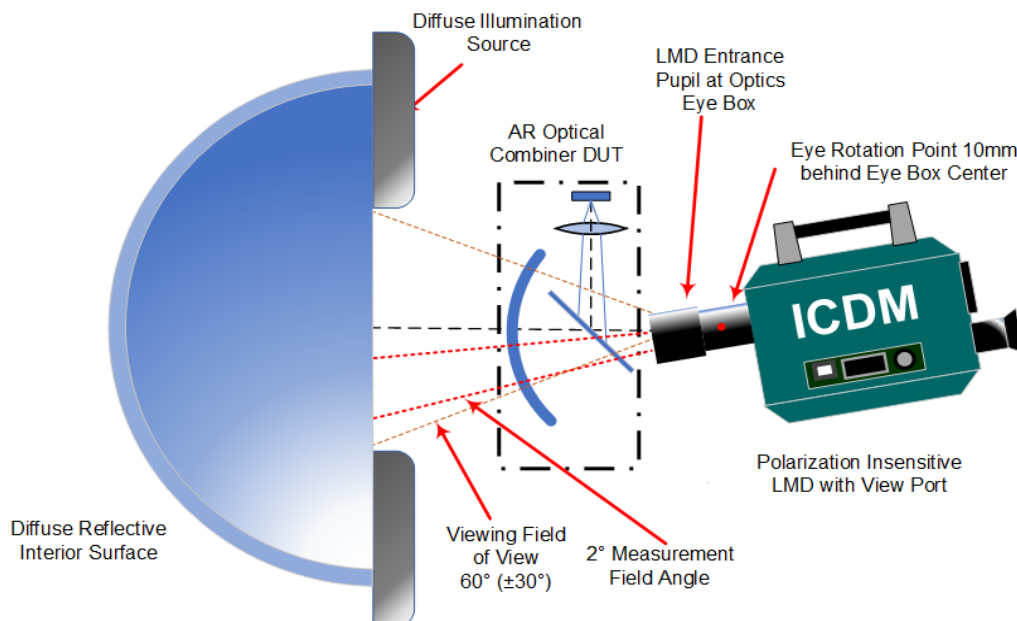


Fig. 8. Off-axis measurements using eye rotation vantage point.



the goniometer center of rotation is 10 mm behind its entrance pupil – i.e., 10 mm further from the NED eyebox. Figure 8 illustrates an off-axis luminance measurement with LMD rotation configured for eye rotation vantage point.

While this configuration will better represent true eye motion, there may be undesired results in the measurement data. Depending on the diameter or, diagonal measure, of the cross-section of the eye box, the LMD rotation about the eye center vantage point may rotate the LMD entrance pupil away from the eye box such that the off-axis measurements decrease more significantly as the NED eye box and the LMD entrance pupil overlap decreases. Thus, the effective FOV may decrease. For this reason, for many NED devices, the eye box diameter is designed to be 10-11 mm. The choice of eye pupil rotation vantage point or eye center rotation vantage point *must* be reported with the measurement and computation results as part of the measurement setup.

PROCEDURE: In addition to the direct on-axis measurement, it may be useful to include measurements at the four corners of the NED field of view (FOV) as shown in Fig. 9, where H and V are the horizontal and vertical, respectively, extents of the NED FOV. When making the additional field measurements, the position of the LMD entrance pupil and the NED eyebox should remain constant for the case for eye pupil rotation vantage point. For the case for Eye Rotation Vantage Point, the LMD entrance pupil will move around within the NED eyebox in a similar manner to movement of the human eye pupil within the eyebox during normal use. Here, it is important that the rotation of the LMD does not allow the entrance pupil to move beyond the NED Virtual Image FOV and allow the illumination source light to bypass internal NED optical elements and enter the LMD aperture. This may create significant inconsistencies in the measurement results. For data collection purposes, the five field points should be labeled as shown in Fig. 8 with #3 in the center of the display FOV, i.e., on the optical axis of the illumination source and the NED DUT, and points 1,3,7 and, 9 in the corners.

Detailed Procedure:

1. Follow the setup procedure above to position the illumination source, the LMD and, the NED DUT.
2. Turn the DUT “ON” and align the center of the display and the eyebox to the illumination source/LMD optical axis.
3. Set the LMD focus on the DUT test image.
4. Turn “OFF” the NED DUT.
5. Measure the luminance, $L_{v,3}$, for the center field point.
 - a. (Optional) Repeat the luminance measurement for the four (or more) remaining field points, $L_{v,1}$, $L_{v,3}$, $L_{v,7}$ and $L_{v,9}$.
6. Return the LMD alignment to the on-axis position.
7. Carefully remove the DUT from the test setup while maintaining the position of the illumination source and LMD.
8. Measure the luminance of the illumination source, $L_{v,IS}$.

Note: If the measured results are low, it may mean that the DUT is diffusing (scattering) or absorbing the ambient illumination. This especially may be the case for the waveguide combiner shown in Fig. 4.

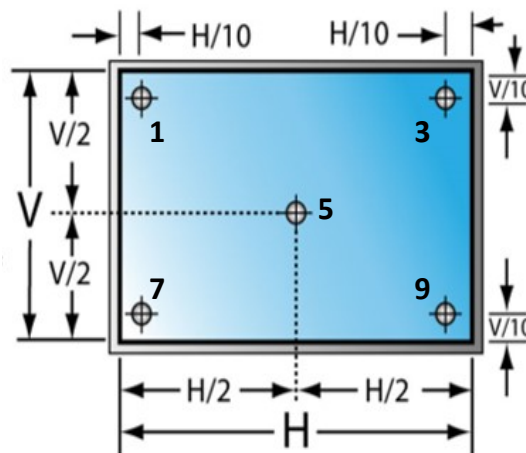


Fig. 9. Five-point field measurement.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

Table 1. Analysis Example:
Luminance measurements

	Position	Value
$L_{v,1}$	U.L.	100.80
$L_{v,3}$	U.R.	109.80
$L_{v,5}$	Center	243.40
$L_{v,7}$	L.L.	111.90
$L_{v,9}$	L.R.	103.80
$L_{v,IS}$	Reference	393.70



ANALYSIS: Calculate the transmittance⁵, $T_{0/3}$, as follows:

$$(1) \quad T_{0/5} = k \cdot \int_{\lambda_1}^{\lambda_2} \frac{L_{v,5}(\lambda)}{L_{v,IS}(\lambda)} \cdot V(\lambda) \cdot D_{65}(\lambda) \cdot d\lambda, \quad k = \frac{100}{\int_{\lambda_1}^{\lambda_2} V(\lambda) \cdot D_{65}(\lambda) \cdot d\lambda}$$

Where $V(\lambda)$ is the CIE standard photometric observer for photopic vision,
 $D_{65}(\lambda)$ is the CIE Standard Illuminant D65,
 λ_1 is the lower wavelength of the visible spectrum range,
 λ_2 and the upper wavelength of the visible spectrum range.

(Optional) Repeat the transmittance computation for the four remaining field points, $L_{v,1}$, $L_{v,3}$, $L_{v,7}$ and $L_{v,9}$.

REPORTING: The following items shall be reported:

- Transmittance, $T_{0/x}$, and spectral radiance, $L_{v,x}(\lambda)$, $L_{v,IS}(\lambda)$ as shown in Table 2.
- Detailed information of the illuminating source.
- Setup details, including LMD and aperture size, eye vantage point and DUT optical axis.

COMMENTS:

- (1) **Number of test points:** This test suite can be performed for a single point on the NED optical axis or, for 5 points, 9 points (3 x 3), or 25 points (5 rows of 5 points evenly distributed), per the interested party's choice. Measurements can vary widely across the virtual image field relative to the center of the virtual image, so there may be a need to measure more than 25 points for color uniformity or MTF measurements.
- (2) **eye relief:** Not all NED devices offer an eye relief of 25 mm. Some may be less, and some may be more. Generally, the eye relief for any NED ranges from a minimum of 16mm (common for normal prescription eyewear) to about 28 mm, allowing for the user's own prescription eyewear clearance.
- (3) **Measurement Distance:** If a less than or equal to 28 mm measurement is not achievable for a NED-LMD combination due to size of the aperture mounting or lens size, then it is not possible to use this particular NED-LMD combination.
- (4) **Center of Rotation for Off-Axis Measurements:** As discussed above, Eye Rotation Vantage Point is a critical factor in the measurement as it will affect the NED transmittance performance over angle and change the effective NED FOV. If the NED eyebox is small (<10 mm), the Eye Pupil Vantage Point configuration should be considered. While the Eye Center Vantage Point may better represent the results with true eye motion, it may reduce the effective FOV of the NED. If the off-axis transmittance results appear suspiciously high, i.e., higher than the on-axis measurements, the LMD may have been rotated beyond the effective FOV of the NED and illumination may be missing internal optical elements. This situation should be corrected.
- (5) **Scattering of Optical Elements:** As noted above, scattering of the ambient illumination during testing by waveguide, holographic (diffractive) optical elements and by haze in some plastic optical elements can cause undesirable results and should be avoided or, further characterized to insure the accuracy and reproducibility of the measurements.

REFERENCES:

- ¹ B. C. Kress, "Optical Architectures for Augmented-, Virtual-, and Mixed-Reality Headsets", SPIE Press, 2020.
- ² D. Cheng, Y. Wang, H. Hua, M. M. Talha, "Design of an optical see-through head-mounted display with a low f-number and large field of view using a freeform prism," Applied Optics, Vol. 48, No. 14, 2009.
- ³ H. Hua, B. Javidi, "A 3D integral imaging optical see-through head-mounted display," Optics Express, Vol. 22, No. 11, 2014.
- ⁴ C. Jang, et al., "Retinal 3D: Augmented Reality Near-Eye Display Via Pupil-Trackd Light Field Projection on Retina," ACM Transactions on Graphics, Vol. 36, No. 6, Article 190, 2017
- ⁵ ASTM D1003-00, "Standard test method for haze and luminous transmittance of transparent plastics," 2000.
- ⁶ ISO 14782:1999(E), "Plastics — Determination of haze for transparent materials," 1999, Reviewed 2015.
- ⁷ BS IEC 63145-22-10:2020, "Eyewear Display-Part 22-1 0: Specific measurement methods for AR type-Optical properties," International Electrotechnical Commission, 2020.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

**Table 2. Reporting Example:
Transmittance Computations**

Transmittance	Position	Measured Luminance
$T_{0/1}$	43.1	U.L.
$T_{0/3}$	43.5	U.R.
$T_{0/5}$	48.2	Center
$T_{0/7}$	43.8	L.L.
$T_{0/9}$	43.3	L.R.
	Reference	$L_{v,IS}$
		393.70



19.11 SEE THROUGH CONTRAST & EFFECTIVE RESOLUTION

ALIAS: Ambient Contrast Modulation, Ambient Michelson contrast, Through Optics MTF

DESCRIPTION: Augmented reality (AR) displays are unique among near-eye displays (NEDs) in that they optically combine the computer-generated (CG) information with the physical world (ambient scene) surrounding the user. There are many methods used in various NEDs to combine the ambient and CG information. Examples of some commonly implemented optical image combiners are given in Section 19.10.

Measuring the ability of a display to properly render detail often is a measurement of high contrasts in small areas. If you are not familiar with techniques for accounting for glare, see Appendix, A2: Stray-Light Management and Veiling Glare. In particular, see A2.1.6: Correcting for Glare with a Replica Mask and A2.2: Accounting for Glare in Small-Area

Measurements. Most of the chapters in this standard describe methods of measuring the contrast of the presented CG images – and many of these methods can be extended to include the contrast of the virtual images provided by near-eye displays. However, this section concentrates on the contrast of the see-through optical systems of augmented reality NEDs – basically the same contrast measurement for any visual optical system such as a camera lens.

Figure 1 illustrates the basic configuration for a NED. The CG information is provided by an imager device that provides the virtual image directed to the wearer's eye. The wearer also views the ambient scene through the optical image combiner (partial reflector in this example) and the protective visor, the combination of which we call the through optics. The virtual image distance is specified by the NED manufacturer and is based on the particular application. For example, a NED designed for the wearer to use while working with their hands – say, looking for a defective device on a circuit board – will present the virtual image at approximately the location of the wearer's hands – about 0.5 meter (2.0 diopter). Whereas a NED or, HMD designed for use by rotorcraft crew personnel will present the virtual image at infinity (0.0 diopter). A measurement of optical contrast of the through optics requires a target or, test pattern be implemented in the ambient scene to measure accurately the contrast and image resolution capabilities of the through optics. As Fig. 1 also indicates, the contrast of the through optics necessarily should be measured at the location of the CG virtual image – the application specific working distance of the NED. The unit, diopter, is introduced here to assist in the design of the measurement setup. The diopter is a unit of optical lens power and is defined as the inverse of focal length, in meters. A lens, for example, that can focus within a short distance requires more optical power than a lens that focuses at some further distance. Likewise, the change in optical power is much greater to change focal lengths that are small than to change focal lengths that are large. Since it would be impractical to locate a test target at infinity to evaluate a NED which is designed to operate with the CG virtual image at infinity, placing the target at, say, 5.0 meters (0.2 diopter) provides measurement results that are within reasonable error limits. Put into human vision terms, 0.2 diopters corresponds to the spectacle lens power required for someone with 20/29 rather than perfect 20/20 visual acuity. Most consumer-type eyewear NEDs are designed to operate with the virtual focus in the range of 0.1 to just under 3.0 diopters. So, for these NED devices, target distances of as little as 3 meters may be acceptable.

APPLICATION: This measurement can be applied to transmissive or emissive stereoscopic near-eye displays that use free-space, waveguide-type or, laser-scanning holographic ambient illumination optical combiners.

SETUP: As defined by these icons, standard setup details apply (§ 3.2):



OTHER SETUP CONDITIONS: (1) **Number of pixels measured:** Typically, in practice, measurements with fewer than 500 pixels are sufficient to achieve adequate reproducibility of the measurements. (2) **Measurement field angle:** The measurement field angle must be less than or equal to 2° so that the lens of the LMD better simulates the human eye. (3)

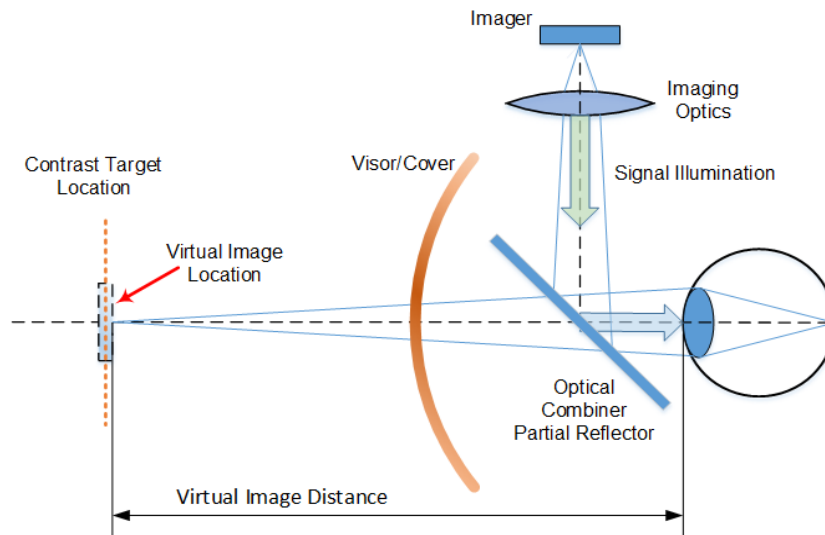


Fig. 1. Tilted half-tone mirror combiner and virtual image location.



Alignment pattern: Use an appropriate test pattern to locate the center of the eyebox. **(4) Background illumination:**

Contrast measurements are extremely sensitive to stray light and vignetting. For the recommended procedures described in following sub-sections, it is highly recommended that all measurements be performed in a darkroom environment in which all light sources other than the target illumination are shut off or, blocked by adequate baffling.

Additional Set-up Details: In this section, two alternative procedures will be discussed: the Slant-Edge Method (section 19.12.1) and the Grill Pattern Method (section 19.12.2). Both are described well in sections 7.7 and 7.8 of this Standard with a good tutorial and comparison of these methods in the appendix B20. Other methods¹ described in Chapter 7 also may be adapted and used for ambient contrast measurements of NEDs. However, these two methods are very closely related and require similar setups and equipment.

Contrast Detection: The measurement of display or, optical contrast may be performed using single and separate black and white targets. However, image resolution only can be determined using targets that contain both black and white sections. In order to measure black and white target elements at the same time, a single element luminance detector such as a spot photometer or, spot radiometer is not practical. Typically, a 2D array LMD such as a CCD array or, a CMOS camera with photopic response is used instead². If you are not very familiar with the use of array light measurement devices, you should review appendix A9 before initial measurements.

Target Presentation: The contrast measurement targets may be presented to the AR NED under test in a number of ways:

- High quality targets may be purchased from specialized vendors,
- High quality transparent film targets that can be back-illuminated also are available,
- Targets may be downloaded or generated on computer and printed out on standard paper or card stock,
- Computer originated targets may be displayed on a large format electronic display such as a computer monitor.

All of these methods have inherent advantages and disadvantages. Regardless of which method is used, it is prudent to make initial measurements of the target resolution and contrast without the NED in the test setup.

High quality purchased targets generally will be robust and will withstand repeated uses and can provide high contrast ratios for NED measurements. Opaque targets require uniform diffuse front illumination. Care must be taken to ensure the illumination indeed is uniform over the measurement area – especially if the illumination is provided from an off-optical axis position. The same care must be taken with printed targets regarding the front illumination. Also, computer printers generally cannot reproduce the full contrast of the original target. Here again, pre-test measurement of the target contrast is necessary. Purchased transparent film targets generally provide excellent contrast and uniform diffuse back illumination may be provided by the apparatus described in section 19.11 for ambient luminance measurements. For large transparent film targets, a high-quality photographic light-table may be used with at least 95% uniformity over the ROI.

When making array-LMD measurements from a display monitor the relative sizes of the display pixels and the array LMD pixels must be considered. This topic is discussed in detail in the appendix A9. Generally, a good “rule of thumb” is that the number of detector pixels should be at least 4 to 10 times the number of display pixels. It is not recommended to attempt to use either front or rear projection devices to present the contrast test patterns as these devices generally cannot adequately reproduce the high contrast of the original.



19.11.1 CONTRAST & EFFECTIVE RESOLUTION: SLANT-EDGE METHOD

PROCEDURE: Figure 2 shows the general test pattern for the slant-edge measurement³. The test pattern is approximately half white and half black with the border between the two halves angled at approximately $6^\circ - 10^\circ$. The region of interest (ROI) should be selected near the image center in an area with good uniformity for each portion of the image. Also, the dimensions of the ROI are determined by the measurement field angle and the target distance. For example, the measurement

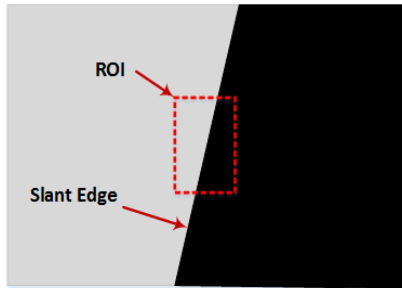


Fig. 2. Slant Edge Test

field angle is $\pm 1^\circ$ and the target distance is 1.0 meter. Thus, the ROI is 24.7 x 24.7 mm by simple trigonometric relationships. Figure 3 illustrates the basic setup for the slant edge method. In the figure, an integrating sphere provides the diffuse light source, like that used in section 19.11. A knife edge attached across the exit port of the integrating sphere provides the slant-edge and a sharp transition from the white light illumination to the opaque portion of the test image. The target distance is the virtual image distance, as illustrated in Fig. 1, subtracting the distance from the imaging sensor to the outer most element of the NED. The NED is mounted on a 2-axis goniometer assembly (θ, ϕ) with the center of mechanical rotation located at either the eye pupil rotation vantage point (EPRVP) or, the eye center rotation vantage point (ECRVP) as shown in the figure. See section 19.1 for comparison of pupil vs. eye Center rotation configurations. The setup illustrated in Fig. 3 will work

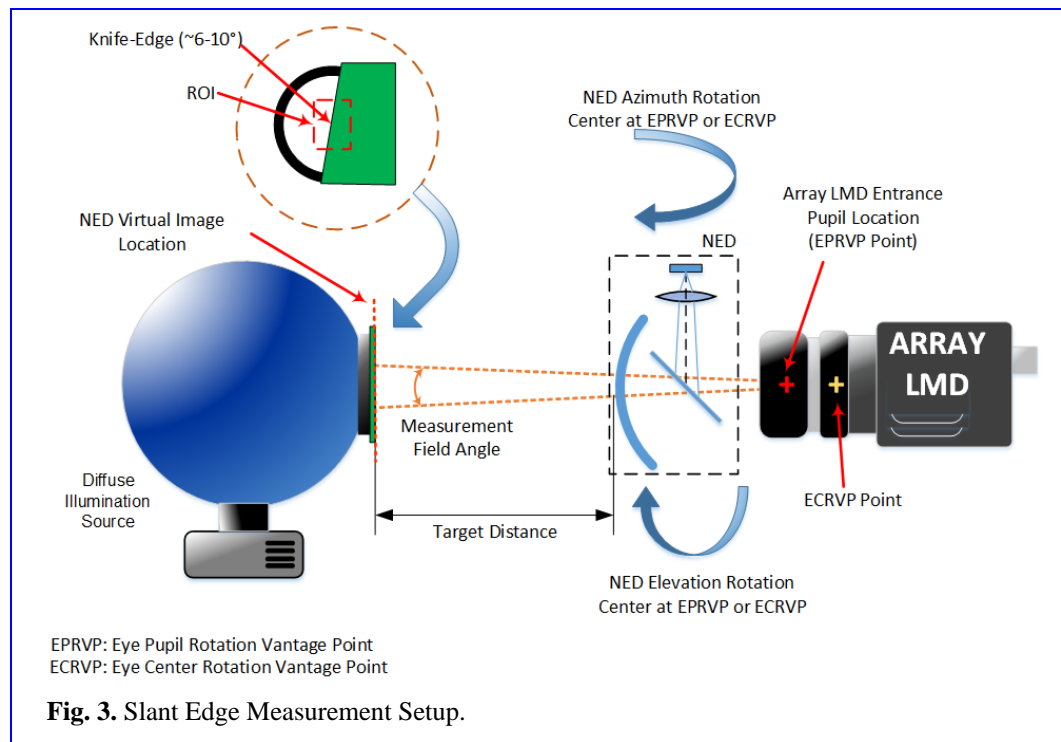


Fig. 3. Slant Edge Measurement Setup.

well with target distances up to about 2.0 meters. However, for larger distances, a much larger integrating sphere is required which may be impractical. For these conditions, the light table backlight or a display monitor may be better choices. For example, at 10.0 meters target distance, the diameter of the measurement field angle would be 349 mm or, about 13.75 inches. As with the LMD in section 19.11, the array LMD requires a field stop to limit the measurement field angle to $\pm 1^\circ$. Some camera lenses may provide an adjustable field stop. If it does not, the effective field stop will be the edge of the last lens forming the image on the array imaging device or, more likely, the edge of the imaging device itself. In either case, the image of the field stop forms an entrance window, typically in front of the camera lens. An aperture of the appropriate diameter placed at or, near, this location will function adequately to limit the measurement field angle.

CAUTION: As with all contrast measurements, the results may be grossly inaccurate unless proper accounting and/or correction is made for *veiling glare*. Appendix A2 is devoted to diagnosing, accounting and/or correcting for various types of stray light situations encountered in typical contrast (and, other) display related measurements and should be reviewed prior to setup calibration and use.

Detailed Procedure:

- 1) With the NED installed in the test setup and turned on, align the NED optical axis along the optical axis of the diffuse light source and the LMD. See Section 19.3 for procedures used to locate the center of the eyebox.
- 2) Adjust the focus of the LMD to the virtual image location of the NED.
- 3) Turn the NED off and adjust the position of the contrast target to the same location as the NED virtual image, i.e., also in focus on the LMD.



- 4) Remove the NED from the test setup, capture the image of the target test pattern.
- 5) Using the capture tools, select 5 or more horizontal lines within the ROI and measure the image gray-scale along each line.
- 6) Follow the procedure detailed in section 7.7.1 to align the transitions of the selected lines and convert the detector pixel count to proportional luminance.
- 7) Follow the procedure detailed in section 7.7.2 to remove aliasing and noise to create the ensemble average of the light and dark regions of the test pattern.
- 8) The global Michelson contrast, C_M , is then calculated from

$$C_M = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}$$

where $\overline{L_W}$ is the ensemble average of the light (white) measurements and $\overline{L_K}$ is the ensemble average of the dark (black) measurements.

- 9) Rotate the knife-edge target by 90° on the diffuse illumination source port and capture another image of the target.
- 10) Use the capture tools to select 5 or more vertical lines within the ROI and measure the gray-scale along each line.
- 11) Repeat steps 3 through 5 to compute the global Michelson contrast for the vertical target orientation.
- 12) Insert the NED into the measurement setup. Return the target orientation to the horizontal position.
- 13) Capture the image of the target through the NED optics.
- 14) Repeat steps 5) through 8) above to measure the horizontal Michelson contrast.

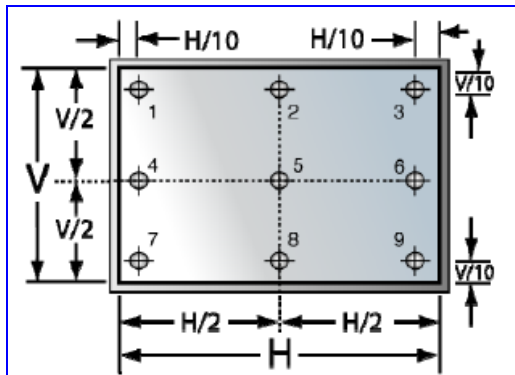


Fig. 4. Nine-Point Field Measurement.

- 15) Rotate the knife-edge target and capture another image of the target and measure the gray-scale of 5 or more vertical lines within the ROI.

- 16) Repeat steps 5 through 8 to compute the Michelson contrast for the vertical target orientation.

- 17) (optional) Adjust the Θ_x and Θ_y position of the NED goniometer mount and repeat steps 3) through 5) above for each of the additional eight off-axis measurement points as shown in Fig. 4, where V and H are the vertical and horizontal extents of the NED virtual image.

The number of off-axis measurement points may be 5, as recommended in section 19.11, 9, or 25. Nine off-axis measurement points is recommended for the contrast measurement set since contrast and/or image resolution variations over the NED field of view may introduce significant usage issues. The setup of Figure 3 above is illustrated in Fig. 5 showing rotation of the NED DUT about the ECRVP - $\Theta_x \approx 10^\circ$.

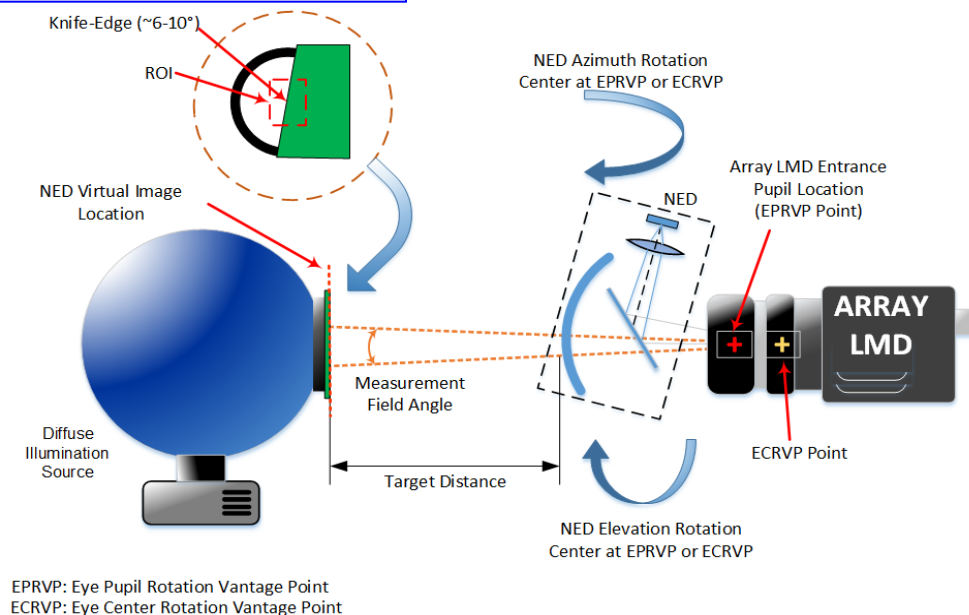


Fig. 5. Off-Axis Measurements Using Eye Rotation Vantage Point.

**ANALYSIS:**

To proceed with the determination of the effective resolution, compute the spatial frequency response (SFR) of the image of the test pattern, $M_T(f)$ ⁴, from the Michelson contrast, C_M , the SFR of the LMD, $M_C(f)$ and, the combined SFR of the test pattern and the LMD, $M_{TOT}(f)$:

$$M_T(f) = C_M M_{TOT}(f) / M_C(f)$$

Following the procedure from section 7.7.1^{5,6}, following Step 4 where aliasing and noise were removed⁷:

- 1) Compute the pixel line spread function, $LSF(p)$, numerically differentiate the pixel luminance determined in Step 4 and resample the luminance to a new function with spacing δp .
- 2) Fourier transform $LSF(p)$ to obtain the SFR.

$$F_K[LSF(p)] = \sum_{n=0}^{N-1} LSF(n \cdot \delta p) e^{-j2\pi kn/N}$$

where, N is the number of sampling points in $LSF(p)$.

- 3) Take the modulus of the Fourier transformed data and obtain the normalized SFR by

$$SFR_k = |F_K[LSF(p)] / F_0[LSF(p)]|$$

where, $F_0[LSF(p)]$ is the DC component.

The result should look something like Fig. 6, showing the spatial frequency response (SFR) vs. inverse pixel.

The resolution, $f(n\%)$, is obtained by finding the spatial frequency at a specified drop of $n\%$ in $M_T(f)$ curve as shown in Fig. 6.

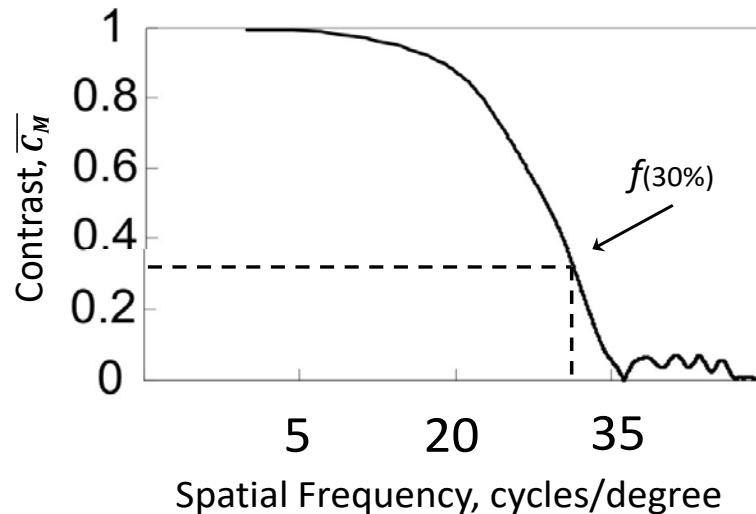


Fig. 6. Example Spatial Frequency Response from Slant-Edge Measurement.

REPORTING: The following items shall be reported:

- a) The type and style of the test target used.
- b) The results of the target test pattern contrast measurements, i.e., without NED.
- c) The number and general location of directional views through the NED, e.g., 1, 5, 9, etc.
- d) The eye vantage point used for off-axis view measurements, e.g., Pupil Rotation, Eye Center Rotation.



- e) For each View direction and pattern orientation (H and V) include $\overline{L_W}$, $\overline{L_K}$ and, $\overline{C_M}$ for both vertical and horizontal measurements.
- f) Include the resolution, the spatial frequency at which the contrast decreased to $n\%$.
- g) For each viewing direction and pattern orientation include any veiling glare correction, S_g , used.
- h) Include a plot of the Michelson contrast, $\overline{C_M}$, vs. spatial frequency similar to the plot shown in Fig.6.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

**Table 1. Reporting Example:
Transmittance Contrast Computations**

Field Position 5 (on-Axis)			Field Position 1 (Upper Left)			(Other Field Positions...)
Target	Slant-Edge	Units	Target	Slant-Edge	Units	Target...
Orientation	Horizontal		Orientation	Horizontal		Orientation...
$\overline{L_{WH}}$	12.9	cd/m ²	$\overline{L_{WH}}$	11.8	cd/m ²	$\overline{L_{WH}}$...
$\overline{L_{KH}}$	0.23	cd/m ²	$\overline{L_{KH}}$	0.56	cd/m ²	$\overline{L_{KH}}$...
$\overline{C_{MH}}$	0.96		$\overline{C_{MH}}$	0.91		$\overline{C_{MH}}$...
$f(30\%)$	29.4	cycles/°	$f(30\%)$	29.2	cycles/°	
Orientation	Vertical		Orientation	Vertical		Orientation...
$\overline{L_{WV}}$	11.1	cd/m ²	$\overline{L_{WV}}$	10.5	cd/m ²	$\overline{L_{WV}}$...
$\overline{L_{KV}}$	0.22	cd/m ²	$\overline{L_{KV}}$	0.49	cd/m ²	$\overline{L_{KV}}$...
$\overline{C_{MV}}$	0.96		$\overline{C_{MV}}$	0.91		$\overline{C_{MV}}$...
$f(30\%)$	29.3	cycles/°	$f(30\%)$	29.2	cycles/°	

COMMENTS:

- (1) **Number of test points:** This test suite can be performed for a single point on the NED optical axis or, for 5 points, 9 points (3 x 3), or 25 points (5 rows of 5 points evenly distributed), per the interested party's choice. Measurements can vary widely across the virtual image field relative to the center of the virtual image, so there may be a need to measure more than 25 points for color uniformity or MTF measurements. A minimum of 9 test points (3 x 3) is recommended for contrast and/or effective resolution measurements for NED devices.
- (2) **Center of rotation for off-axis measurements:** As discussed above and in section 19.11, Eye Rotation Vantage Point is a critical factor in the measurement as it will affect the NED transmittance performance over angle and change the effective NED FOV. If the NED eyepoint is small (<10 mm), the Eye Pupil Vantage Point configuration should be considered. While the Eye Center Vantage Point may better represent the results with true eye motion, it may reduce the effective FOV of the NED. If the off-axis contrast results appear suspiciously high, i.e., higher than the on-axis measurements, the NED may have been rotated beyond the effective FOV and illumination may be missing internal optical elements. This situation should be corrected.
- (3) **Scattering of optical elements:** As noted above, scattering of ambient illumination during testing by waveguide, holographic (diffractive) optical elements and by haze in some plastic optical elements⁸ can cause undesirable results and should be avoided or, further characterized to ensure the accuracy and reproducibility of the measurements. All optical elements of the setup should be evaluated for veiling glare and with each View direction of the NED. Appendix A2 should be consulted for information regarding veiling glare and means to prevent or account for veiling glare.
- (4) **New, updated, or improved slant edge test method:** If chapter 7 contains a new, updated, or improved test method for the slant edge measurement and analysis, the reader should review the new method to see if it offers any improvements over the method described in this section. Please note that the methods in chapter 7 generally apply to measurements of direct view or projected displays and not near-eye displays and may require some adaptation for use with near-eye displays.

REFERENCES:

¹ K. Masaoka, M. Sugawara, Y. Nojiri, "Multidirectional MTF measurement of digital image acquisition devices using a Siemens star," Proc. SPIE 7537, Digital Photography VI, 75370V, 18 January 2010.

² ISO 17321-1, "Graphic Technology and Photography - Color characterization of digital still cameras (DSCs) using color targets and spectral illumination", First edition, International Organization for Standardization (1999).



³ K. Masaoka, “Real-time modulation transfer function measurement system,” Proc. SPIE 10943, Ultra-High-Definition Imaging Systems II, 1094309, 1 March 2019.

⁴ ISO 12233, "Photography - Electronic still-picture cameras – Resolution measurements", First edition, International Organization for Standardization (2000).

⁵ ISO 12233, "Photography - Electronic still-picture cameras - Resolution measurements", First edition, International Organization for Standardization (2000).

⁶ ISO 17321-1, "Graphic Technology and Photography - Colour characterisation of digital still cameras (DSCs) using colour targets and spectral illumination", First edition, International Organization for Standardization (1999).

⁷ D. L. Donoho, IEEE Trans. Inform. Theory Vol. 41, p. 613 (1995).

⁸ ISO 14782:1999(E), “Plastics — Determination of haze for transparent materials,”1999, Reviewed 2015.



19.11.2 CONTRAST & EFFECTIVE RESOLUTION: GRILLE METHOD

ALIAS: Grille contrast, Michelson contrast

DESCRIPTION: An alternative method for evaluating image contrast and effective spatial resolution is the Grille Pattern method, described in detail in sections 7.2 (Contrast) and 7.8 (Effective Resolution.) This method utilizes test patterns of several cycles of bright/dark (white/black) alternating bars of equal pitch as illustrated in Fig. 1. Fig. 1 shows three grille pattern test charts with a) low-, b) medium- and c) high-spatial frequencies. Michelson contrast is measured on each of the test patterns and reported. Generally, contrast decreases as spatial frequency increases since optical blur diminishes the sharpness of the light/dark transition such that a line scan across the multi-bar patterns produces a sinusoidal response rather than the sharp on-off pattern of the lower spatial frequency pattern as illustrated in Fig. 2. This spatial frequency measurement is

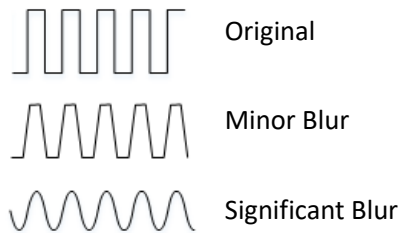


Fig. 2. Image blur effect on scan lines

often referred to as modulation

transfer function (MTF) since the results generally are quite similar. Strictly speaking, for MTF measurements, sinusoidal patterns are used for all spatial frequency ranges, rather than the light/dark bar patterns for grille tests. Appendix B20 provides a good discussion on the grille pattern and MTF evaluations and a comparison of the two approaches. Typically, grille method is used for electronically produced imagery since image resolution ultimately is limited by the number and size of the pixels. Sinusoidal patterns are used for pure optical systems since the light wave variations generally are analog in nature. However, grille-type charts are often used for pure optical systems as well since the bar patterns are easier to produce with uniform contrast than

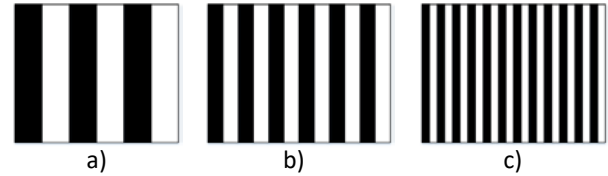


Fig. 1. Grille test patterns for a) low-, b) medium- and c) high-spatial frequencies.

sinusoidal patterns. Figure 3 illustrates another popular grille test pattern with a linearly varying spatial frequency. This target is convenient in that a single target provides results for a range of spatial frequencies, rather than three or more targets. However, these targets are more difficult to produce accurately and since each bar varies in width, the spatial frequency depends solely on the accuracy of the width of each bar and not on the pitch of each light/dark pair. Fig. 4 illustrates another commonly used grille-type target used for display and pure optical

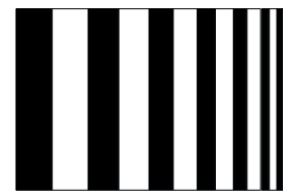


Fig. 3. Use of linearly varying spatial frequency grille pattern is not recommended.

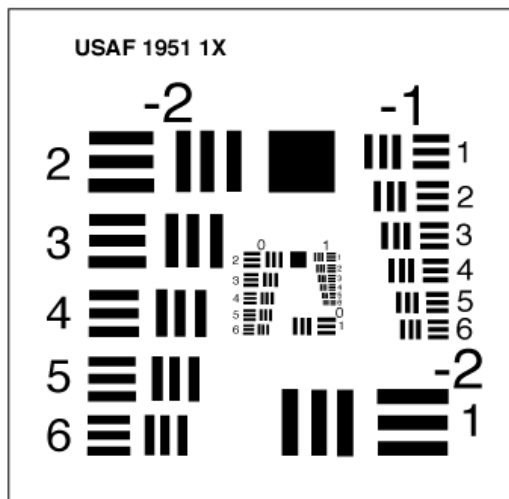


Fig. 4. USAF multi-spatial frequency resolution test chart.

spatial frequency measurements. The USAF resolution target provides bar patterns over 24 different spatial frequencies allowing the same chart to be used for a wide range of optical or, display systems. Also, the chart provides the bar patterns in both vertical and horizontal orientations so that the chart does not need to be rotated during the test.

When choosing a particular grille test pattern chart for use as the contrast target, care must be taken in selecting the appropriate size and spatial frequency range of the test pattern. The low, medium, high patterns in Fig. 1 will provide only three data points for contrast vs. spatial frequency plots. This may be sufficient if the three patterns cover the range of visual acuity. Maximum human visual acuity is about 30 cycles/degree – corresponding to Snellen 20/20. Unlike cameras, human visual acuity decreases slightly at very low spatial frequencies starting at about 6 cycles/degree¹. Thus, the spatial frequency range should cover from ~6 to 30+ cycles/degree. The physical size of the target test pattern depends on the target distance which, in turn, depends on the NED virtual image location by design. For example, if the target distance is 1 meter, then the target spatial frequency range should from about 0.34 to 1.72 lp/mm (6 to 30 cycles/degree.) However, if the



target distance is 10 meters, the 6 cycles/degree pattern would be only 0.034 lp/mm - requiring the target test pattern to be 10x in size.

If using the USAF multi-range target test pattern as shown in Fig. 4, it is possible to have more data points over the human visual acuity range. The spatial frequency (lp/mm) for the USAF target is determined from²

$$lp/mm = 2^{Group+(Element-1)/6}$$

Thus, with a target distance of 1 meter, the human visual acuity range is covered using group -2, element 3 to group 0, element 6 – providing up to 16 data points for the contrast vs. spatial frequency plot.

CAUTION: As with all contrast measurements, the results may be grossly inaccurate unless proper accounting and/or correction is made for *veiling glare*. Appendix A2 is devoted to diagnosing, accounting and/or correcting for various types of stray light situations encountered in typical contrast (and, other) display related measurements and should be reviewed prior to setup calibration and use. A quick diagnosis of veiling glare is illustrated in Fig. 5. Following image capture of the target grille test pattern, if the image appears as shown in Fig. 5 with a “fading” of the grille pattern bars in some portion of the captured image, this probably is the result of veiling glare and must be corrected before proceeding with further contrast or, effective resolution evaluations. However, veiling glare can vary over the image, and generally needs to be corrected locally within the ROI.



Fig. 5. Grille pattern showing effect of veiling glare.

SETUP CONDITIONS: Figure 6 illustrates the basic setup for the grille pattern method. The setup essentially is the same as that for the slant-edge method described in section 19.11.1 with the knife-edge replaced by a transparent film version of one of the grille test patterns shown in Figs. 1 and 4. Most commercially available test targets are available in either opaque

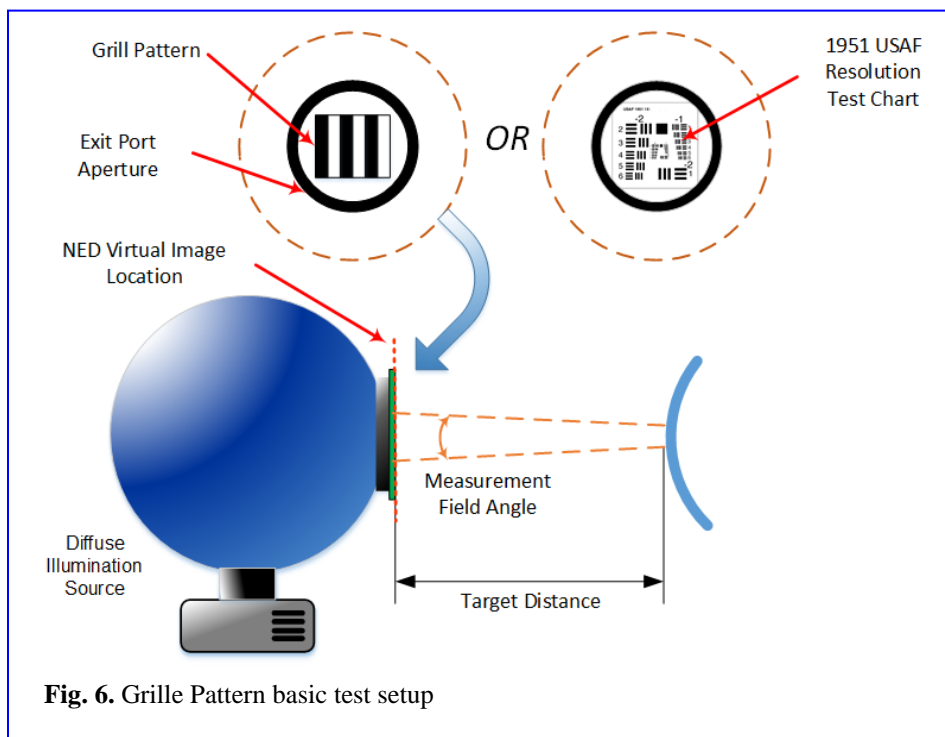


Fig. 6. Grille Pattern basic test setup

(diffuse black patterns on diffuse white background) or transparent film (diffuse black patterns on transparent film). Film targets provide a setup configuration most resembling that of the knife-edge target described in section 19.11.1 and are depicted in Fig.6. Use of opaque targets requires front illumination from an off-axis diffuse illumination source. Note that for the standard bar patterns shown in Fig. 1, the pattern must be rotated after each captured image of the target and re-analyzed to obtain results for both the vertical and horizontal ranges of the NED optics. When using the USAF test chart shown in Fig. 4, the test chart does not require physical rotation since it contains bar patterns arranged for both vertical and horizontal measurements.

When setting up the test targets, make sure that at least two or, more elements are within the Measurement field of view for any single image capture. As noted above, it is essential that the test pattern target be sized appropriately so that the spatial frequency range covers the human visual acuity range. The spatial dimensions of the test patterns will need to increase as the target distance increases such the angular spatial frequency (cycles/degree) range remains the human visual acuity range. Most commercially available test targets are available in a range of sizes. The USAF test chart, for example, is available in sizes up to 36 x 42 inches for large target distance measurement setups.

As with all contrast and effective resolution measurements, it is prudent to measure the contrast and SFR of the target test patterns prior to inserting the NED in the test setup. This assures the integrity and accuracy of the NED measurements that follow. Both vertical and horizontal pretest measurements should be made. If a large screen display monitor is used for large target distance measurements, the preliminary, no-NED, measurements also may assure that the



number of detector pixels relative to display pixels within the measurement field angle is sufficiently high to avoid aliasing and other sampling artifacts especially when measuring the SFR. Figure 7 illustrates an example case where the number of detector pixels to the number of display pixels was insufficient resulting in modulation of the contrast (MTF) vs spatial frequency measurement results compared with the actual MTF of the optical system (d is the detector size). Also, large screen monitors produce a lot of illumination over a wide field of view. Extra care should be taken to insure against unwanted reflections of nearby equipment interfering with contrast measurements.

PROCEDURE: The following procedure somewhat follows that described in section 7.2. With an array LMD with photopic response, measure luminance profiles for both horizontal and vertical grille patterns subject to above setup conditions. Obtain the net signal S as a function of distance with any background subtracted (this is the background inherent in the detector if a nonzero signal exists for no light input). A correction for veiling glare S_g must be made (see A2 Stray-Light Management & Veiling Glare).

- 1) With the NED installed in the test setup and turned on, align the NED optical axis along the optical axis of the diffuse light source and the LMD. See Section 19.3 for procedures used to locate the center of the eyebox.
- 2) Adjust the focus of the LMD to the virtual image location of the NED.
- 3) Turn the NED off and adjust the position of the contrast target to the same location as the NED virtual image, i.e., also in focus on the LMD.
- 4) Remove the NED from the test setup, capture the image of the target test pattern.
- 5) Using the capture tools, select three or more horizontal line pairs within the measurement field angle and measure the image gray-scale along each line.
- 6) Perform a running average (moving-window average filter, see B18 for details) of each luminance profile where the averaging window width is as close as possible to the pixel pitch as rendered by the LMD³. For an array detector this is however many array detector pixels in a row or column are needed to cover one display pixel (if an electronic display is used to present the target test patterns). If a commercial opaque or transparent film target is used, the window width should not exceed $\frac{1}{2}$ of the grille pitch.
- 7) From the resulting modulation curve determine (1) the net level of the grille black lines $S_K = S_d - S_g$, where S_d is the minimum of the grille black lines, and (2) the net level of the grille white lines between the specified black lines $S_W = S_h - S_g$, where S_h is the average maximum of the grille white lines.
- 8) Compute the Michelson contrast, C_M , calculated from

$$C_M = \frac{S_W - S_K}{S_W + S_K}, \text{ where}$$

$$\left\{ \begin{array}{l} S_g = \text{glare correction} \\ S_h = \text{white line average (high)} \\ S_d = \text{black line average (dim)} \\ S_W = \text{net white value} \\ S_K = \text{net black value} \\ C_M = \text{Michelson contrast} \end{array} \right.$$

- 9) Compute the ensemble average for however many scan lines used in the captured image of the grille test pattern from

$$\overline{C_M} = \frac{\overline{L_W} - \overline{L_K}}{\overline{L_W} + \overline{L_K}}, \text{ where}$$

$\overline{L_W}$ is the ensemble average of the light (white) measurements, S_W , and $\overline{L_K}$ is the ensemble average of the dark (black) measurements, S_K .

- 10) If a single-orientation Grille bar pattern is used, rotate the target pattern by 90° and capture the image of the test pattern.
- 11) Repeat steps 5) through 9) above and record the results as shown in Table 1.
- 12) If a single spatial frequency test pattern is used, replace test pattern with at least two other spatial frequency patterns and repeat steps 5) through 11). Record the $\overline{C_{MH}}$ and $\overline{C_{MV}}$ for each spatial frequency test pattern.

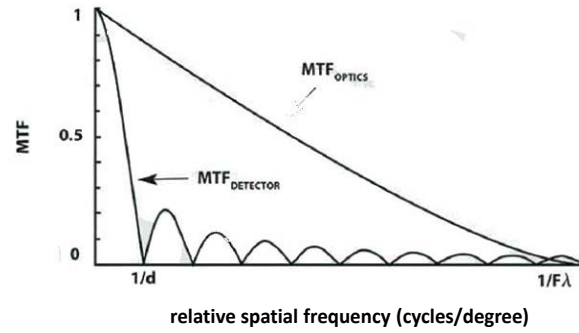


Fig. 7. Example of contrast response affected by insufficient detector pixel number.



- 13) Insert the NED back into the measurement setup on the goniometer mounts. Turn the NED on and align the center of the display and the eyebox to the Target/LMD optical axis. See Section 19.3 for procedures used to locate the center of the eyebox.
- 14) Capture the image of the first target pattern in the first orientation.
- 15) Repeat steps 5) through 9) and then repeat steps 5) through 11) again for the second target orientation and repeat step 9).
- 16) Record the results.
- 17) (optional) Adjust the Θ_x and Θ_y position of the NED goniometer mount preferably using the eye rotation vantage point method (19.5), capture the target image and repeat steps 5) through 12) above for each of the additional eight off-axis measurement points as shown in Fig. 8, where V and H are the vertical and horizontal extents of the NED virtual image.
- 18) Record the full results as shown in example Table 2.
- 19) Determine the spatial frequency for each grille pattern in terms of cycles/degree.
- 20) Plot \bar{C}_{MH} and \bar{C}_{MV} for each spatial frequency grille pattern, pattern orientation and off-axis viewpoint as shown in Fig. 9. Include the No-NED (CMH/V T) reference measurements.

—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

**Table 1. Data Collection results:
Test Target Contrast**

Orientation	Horizontal	Units
Grille	Low	
Glare, S_g	0.08	cd/m ²
\bar{L}_{WH}	13.8	cd/m ²
\bar{L}_{KH}	0.14	cd/m ²
\bar{C}_{MH}	0.98	
Orientation	Vertical	
Grille	Low	
Glare, S_g	0.08	cd/m ²
\bar{L}_{WV}	11.7	cd/m ²
\bar{L}_{KV}	0.12	cd/m ²
\bar{C}_{MV}	0.98	

REPORTING: The following items shall be reported:

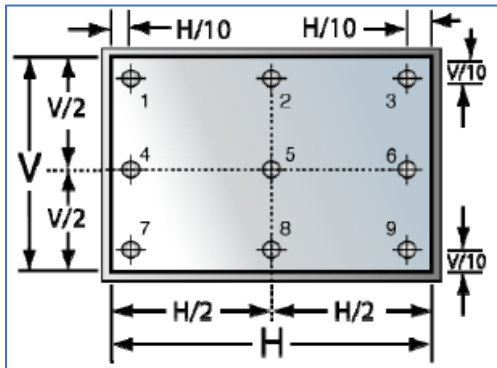


Fig. 8. Nine-Point Field Measurement.

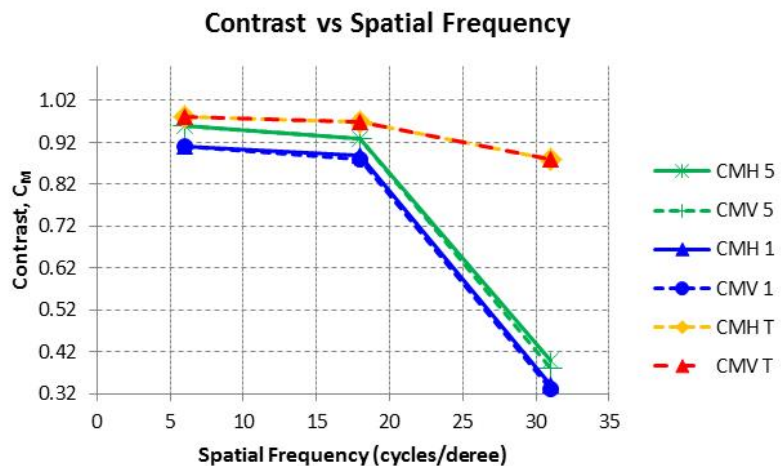


Fig. 9. Example Contrast vs. Spatial Frequency Plot

- a) The type and style of the test target used.
- b) The number of spatial frequency values tested and the specific spatial frequencies.
- c) The number and general location of directional views through the NED, e.g., 1, 5, 9, etc.
- d) The results of the target test pattern contrast measurements, i.e., without NED.
- e) The eye vantage point used for off-axis view measurements, e.g., pupil rotation, eye center rotation.
- f) For each viewing direction and spatial frequency include \bar{L}_W , \bar{L}_K and, \bar{C}_M for both vertical and horizontal measurements.
- g) For each viewing direction, spatial frequency and pattern orientation, include the veiling glare correction, S_g , used.

COMMENTS:

- (1) **Number of test points:** This test suite can be performed for a single point on the NED optical axis or, for 5 points, 9 points (3 x 3), or 25 points (5 rows of 5 points evenly distributed), per the interested party's choice. Measurements can vary widely across the virtual image field relative to the center of the virtual image, so there may be a need to measure more than 25 points for color uniformity or MTF measurements. A minimum of 9 test points (3 x 3) is recommended for contrast and/or effective resolution measurements for NED devices.



—SAMPLE DATA ONLY—

Do not use any values shown to represent expected results of your measurements.

**Table 2. Reporting example:
Transmittance contrast computations**

Field Position 5 (on-Axis)			Field Position 1 (Upper Left)			(Other Field Positions...)
Orientation	Horizontal	Units	Orientation	Horizontal	Units	Orientation...
Grille	Low		Grille	Low		Grille...
Glare, Sg	0.09	cd/m ²	Glare, Sg	0.11	cd/m ²	Glare, Sg...
$\overline{L_{WH}}$	12.9	cd/m ²	$\overline{L_{WH}}$	11.8	cd/m ²	$\overline{L_{WH}}$...
$\overline{L_{KH}}$	0.23	cd/m ²	$\overline{L_{KH}}$	0.56	cd/m ²	$\overline{L_{KH}}$...
$\overline{C_{MH}}$	0.96		$\overline{C_{MH}}$	0.91		$\overline{C_{MH}}$...
Orientation	Vertical		Orientation	Vertical		Orientation...
Glare, Sg	0.09	cd/m ²	Glare, Sg	0.11	cd/m ²	Glare, Sg...
$\overline{L_{WV}}$	11.1	cd/m ²	$\overline{L_{WV}}$	10.5	cd/m ²	$\overline{L_{WV}}$...
$\overline{L_{KV}}$	0.22	cd/m ²	$\overline{L_{KV}}$	0.49	cd/m ²	$\overline{L_{KV}}$...
$\overline{C_{MV}}$	0.96		$\overline{C_{MV}}$	0.91		$\overline{C_{MV}}$...
Grille	Medium		Grille	Low		Grille...
Glare, Sg	0.09	cd/m ²	Glare, Sg	0.11	cd/m ²	Glare, Sg...
$\overline{L_{WH}}$	12.1	cd/m ²	$\overline{L_{WH}}$	11.0	cd/m ²	$\overline{L_{WH}}$...
$\overline{L_{KH}}$	0.44	cd/m ²	$\overline{L_{KH}}$	0.64	cd/m ²	$\overline{L_{KH}}$...
$\overline{C_{MH}}$	0.93		$\overline{C_{MH}}$	0.89		$\overline{C_{MH}}$...
Orientation	Vertical		Orientation	Vertical		Orientation...
Glare, Sg	0.09	cd/m ²	Glare, Sg	0.11	cd/m ²	Glare, Sg...
$\overline{L_{WV}}$	10.3	cd/m ²	$\overline{L_{WV}}$	9.60	cd/m ²	$\overline{L_{WV}}$...
$\overline{L_{KV}}$	0.37	cd/m ²	$\overline{L_{KV}}$	0.61	cd/m ²	$\overline{L_{KV}}$...
$\overline{C_{MV}}$	0.93		$\overline{C_{MV}}$	0.88		$\overline{C_{MV}}$...
Grille	High		Grille	Low		Grille...
Glare, Sg	0.09	cd/m ²	Glare, Sg	0.11	cd/m ²	Glare, Sg...
$\overline{L_{WH}}$	4.60	cd/m ²	$\overline{L_{WH}}$	4.30	cd/m ²	$\overline{L_{WH}}$...
$\overline{L_{KH}}$	1.95	cd/m ²	$\overline{L_{KH}}$	2.11	cd/m ²	$\overline{L_{KH}}$...
$\overline{C_{MH}}$	0.40		$\overline{C_{MH}}$	0.34		$\overline{C_{MH}}$...
Orientation	Vertical		Orientation	Vertical		Orientation...
Glare, Sg	0.09	cd/m ²	Glare, Sg	0.11	cd/m ²	Glare, Sg...
$\overline{L_{WV}}$	4.40	cd/m ²	$\overline{L_{WV}}$	4.10	cd/m ²	$\overline{L_{WV}}$...
$\overline{L_{KV}}$	1.98	cd/m ²	$\overline{L_{KV}}$	2.06	cd/m ²	$\overline{L_{KV}}$...
$\overline{C_{MV}}$	0.38		$\overline{C_{MV}}$	0.33		$\overline{C_{MV}}$...

- (2) **Number of spatial frequency measurement points:** For any useful measurement of effective resolution, at least three spatial frequencies should be measured with grille pattern targets. However, as shown in Fig. 1, only three spatial frequency data points may not be sufficient to characterize the SFR of the NED. Additional spatial frequency grille patterns may be needed or, a target such as the USAF resolution chart may be used. The USAF target provides up to 16 spatial frequency data point covering the human visual acuity range.
- (3) **Center of rotation for off-axis measurements:** As discussed above and in section 19.5, eye rotation vantage point is a critical factor in the measurement as it will affect the NED transmittance performance over angle and change the effective NED FOV. If the NED eyebox is small (<10 mm), the eye rotation vantage point may significantly reduce the effective eyebox for off-axis measurements. If this situation occurs, the extent of the off-axis field points may need to be reduced to provide sufficient eyebox to make these measurements. Also, for extreme cases, eye pupil vantage point configuration may be considered. While the eye center vantage point may better represent the results with true eye motion, it may reduce the effective FOV of the NED. If the off-axis contrast results appear suspiciously high, i.e., higher than the on-axis measurements, the NED may have been rotated beyond the effective FOV and illumination may be missing internal optical elements. This situation should be corrected.
- (4) **Scattering of optical elements:** As noted above, scattering of ambient illumination during testing by waveguide, holographic (diffractive) optical elements and by haze in some plastic optical elements⁴ can cause undesirable results and should be avoided or, further characterized to ensure the accuracy and reproducibility of the measurements. All optical elements of the setup should be evaluated for veiling glare and with each viewing direction of the NED. Appendix A2 should be consulted for information regarding veiling glare and means to prevent or account for veiling glare.



- (5) **Target spatial frequency:** As noted above, the target test patterns as viewed through the NED are measured in units of cycles/degree. Care must be taken when sizing the target test pattern, specified in lp/mm, to provide adequate coverage of the human visual acuity range – ~6 to 30 cycles/degree – at whatever target distance is required according to the specified NED virtual image distance.

REFERENCES:

¹ B. C. Kress, “Optical Architectures for Augmented-, Virtual-, and Mixed-Reality Headsets”, SPIE Press, 2020.

² US MIL-STD-150A.

³ B. Kaur, J. Olson, and E. A. Flug, “Display MTF Measurements Based on Scanning and Imaging Technologies and Its Importance in the Application Space,” Proc. SPIE 9820, Infrared Imaging Systems: Design, Analysis, Modeling, and Testing XXVII, 98200Y, 3 May 2016.

⁴ ISO 14782:1999(E), “Plastics — Determination of haze for transparent materials,” 1999, Reviewed 2015.



20. HIGH DYNAMIC RANGE (HDR)

This chapter of the IDMS is a recent addition. The ICDM feels that it is important for the IDMS to quickly begin to address some of the unique characteristics and the challenging metrology for a new class of displays, often referred to as ‘High Dynamic Range’ or ‘HDR’ displays. The subject matter is complex and the displays in this category are experiencing rapid evolution. As such, more than other chapters in the IDMS, it should be expected that this chapter will evolve, and the measurement methods to be outlined may be updated as other standards become better defined as the technology matures. This chapter is a first release of information and should therefore not be considered exhaustive or complete.



20.1 INTRODUCTION AND BACKGROUND

HDR has various meanings in industry and usage of this term is not always consistent. It is not the ICDM's purpose, nor is it possible, to define what is or is not an HDR display in the context of performance. Therefore, the applicability of the concepts in this chapter is universal and may be applied to any display that accepts the **IDMS HDR Test Signal** as described later in this chapter.

HDR Metrology

Many stakeholders use the expression HDR to highlight and differentiate new capabilities of modern display technology. These include content creators (such as the movie industry), broadcasters, and the display industry. Certain thresholds for peak luminance, color gamut, contrast capability, and rendered bit depth have been set to certify HDR displays with compliance logos. Some displays that are not marketed as HDR may nevertheless have some of these new capabilities. The ICDM does not set performance thresholds for HDR compliance; that is outside the scope of this organization.

In this chapter, concepts will be defined for making HDR measurements based simply on the premise that the **IDMS HDR Test Signal** is used to perform them. Within the context of this chapter, ‘HDR’ describes a display with the ability to recognize and work with the **IDMS HDR Test Signal**.

The display industry often uses the expression ‘SDR’ (Standard Dynamic Range) to differentiate HDR displays from others. The reader is advised that usage of the term SDR is not consistent, nor is it well defined. A display referred to as SDR might have a limited capability envelope (e.g., in terms of luminance or color gamut), however, displays identified as SDR do not necessarily have any limitations. Therefore, from a metrology viewpoint the use of the expressions ‘SDR Display’ and ‘HDR Display’ are confusing and undefined. For ‘HDR Metrology’ in this chapter we confine our context to a ‘Display’ in response to the **IDMS HDR Test Signal**.

It is important to note that the ICDM strives to make IDMS HDR metrology methods independent of display technology, while developing robust methods that allow for advances and future capability. This chapter lays the foundation for future measurements.

HDR Tutorial

To learn more about HDR in general and to understand more than the initial set of display response **Interdependencies** defined here and in individual measurements, please refer to the HDR tutorial in appendix B33 of this document. The HDR tutorial also provides useful background information to help better understand the concept of the HDR ecosystem. It also demonstrates why measurements have to be taken with great care and full awareness of the **Interdependencies**.

20.1.1 TERMS AND DEFINITIONS

DESCRIPTION

This section explains generalized terms and their specific use. Outside the context of the IDMS, these terms may have slightly different or broader definitions. In order to lower confusion and increase the clarity of a complex subject, these specific definitions have been carefully applied to the text. Throughout the chapter these terms will be written in **bold**.



Display-Referred

Display-Referred is a concept, whereby the signal describes a **Theoretical Display**. The **Display-Referred** signal represents the intent of the content creator. A **Display-Referred** signal requires a definition of the non-linearity, min/max luminance, and the color encoding of the signal container. The encoded signal values can be directly transformed to absolute CIE XYZ. The **IDMS HDR Test Signal** in this chapter is **Display-Referred**.

IDMS HDR Test Signal

The **IDMS HDR Test signal** refers to the test signal as defined in section 20.1.5. There are also other types of HDR signals defined in the industry. For the purpose of controlled metrology, a single set of signal parameters is used. This signal is unique compared to other signals described in the IDMS in that it is **Display-Referred**. The signal includes defined parameters for minimum and maximum luminance as well as color primaries. It represents a fixed color gamut volume. Signal identification metadata is used (ST 2084, BT.2020 system colorimetry) to communicate the required parameters to the DUT. The encoded signal values can be directly transformed to absolute CIE XYZ. Additional **HDR Static Metadata** or **HDR Dynamic Metadata** may alter the color mapping of the display system under test. The **IDMS HDR Test Signal** has ST 2086 **HDR Static Metadata** assigned to fixed values. Other metadata is not used in the test signal at this time.

Interdependencies

In metrology that investigates a potential cause-and-effect relationship, additional variables that influence the results can exist. In this document, the term **Interdependencies** is used to refer to variables which affect the response of a display to the **IDMS HDR Test Signal** and are not part of the direct signal display relationship. Examples for such interdependencies can be found in section 20.1.3.

Electro-Optical Transfer Function (EOTF)

EOTF defines the non-linear relationship between signal code values and the luminance response. The **EOTF** together with the min/max luminance and the color system of the signal container in a **Display-Referred** signal defines the expected optical response to each pixel value.

Perceptual Quantizer (PQ)

The **Perceptual Quantizer (PQ)** describes a specific **EOTF** for a luminance range between zero and 100% stimulus which is encoded from 0 to 10,000 cd/m². The **PQ EOTF** is quantized into equal perceptual intervals following detectability thresholds of the human visual system in a bipartite field. **PQ** is the **EOTF** used in the **IDMS HDR Test Signal**. Other HDR **EOTFs** exist but are not yet covered in this document. The **PQ EOTF** is standardized in SMPTE ST.2084^[5] and ITU-R Rec. BT.2100^[2].

HDR Static Metadata

HDR Static Metadata provides additional information to be used for display rendering. It does not change on a frame-by-frame or scene-by-scene basis. SMPTE ST 2086^[5] defines static metadata that describes the color volume of the mastering display. CTA 861.3^[4] describes the transmission of this metadata over HDMI. This static metadata is utilized by the **IDMS HDR Test Signal**. Additional static metadata describing other attributes of mastered content exists. The **IDMS HDR Test Signal** does not use these values. See the tutorial for more details.

HDR Dynamic Metadata

Dynamic metadata provides auxiliary frame-by-frame or scene-by-scene information that may be used for display rendering on the DUT. Dynamic metadata is not used in the **IDMS HDR Test Signal**.

Hybrid Log Gamma (HLG)

HLG is an alternative HDR signaling system defined in BT.2100^[2]. It includes a set of non-linear equations including an **EOTF** which allows for the rendering of HDR video on a broad range of displays with different performance characteristics. **HLG** is not **Display-Referred** and therefore **HLG** does not apply to the **IDMS HDR Test Signal** used in this chapter. More information on **HLG** can be found in the Appendix B33.

Theoretical Display

The term **Theoretical Display** refers to the concept of a theoretically perfect display. The **Display-Referred IDMS HDR Test Signal** would be directly realized by this display in real-time. Every pixel of every frame would be correctly rendered in color, position, and time. At this time, no technology is capable of the performance required to be a **Theoretical Display**.



HDR Display Under Test (HDR DUT)

The **HDR DUT** is a physical display that is receiving the **IDMS HDR Test Signal**. It is likely that the **HDR DUT** is incapable of reproducing the entire **Display-Referred IDMS HDR Test Signal** at the same fidelity as a **Theoretical Display**. It may perform perceptual image rendering, changing signal encoded values to other values in an attempt to perform a proprietary perceptual match. There is no correct method for perceptual rendering. Different systems will prioritize different perceptual components such as luminance, color saturation, hue, contrast, etc. The **HDR DUT** may provide different modes of operation. Some modes may perform perceptual rendering, others may provide a colorimetric match within their capability envelope.

Tone Mapping

This document uses a broad definition of the common term **Tone Mapping**. An **HDR DUT** will likely have a performance envelope less than the **IDMS HDR Test Signal**. The mapping of the **IDMS HDR Test Signal** to the performance envelope of a display is often referred to as **Tone Mapping**. This may include dynamic range clipping or roll-off, perceptual color rendering, or other forms of color gamut mapping and is likely dependent on the display mode. An **HDR DUT** may use different static and/or dynamic metadata as input to the **Tone Mapping** algorithms.

20.1.2 BACKGROUND

The fundamental methods elsewhere in IDMS have been developed to test any display system that accepts a three-component RGB input signal. The methods treat the display as a ‘black box’ and measure the behavior of the display in response to that signal. While the signal delivered to the display may conform to a particular standard or the display may expect a specific standard, the methods are independent of such definition. The RGB test patterns used for these measurements are simply red, green, and blue signal levels. This type of signal is relative if no additional context is provided (such as a signal standard that defines the min and max luminance, **EOTF**, white point, and color gamut), it is not **Display-Referred**. It provides a simple uncomplicated cause and effect relationship between the signal input and the light output from the DUT.

A majority of the fundamental methods in the IDMS were originally developed at a time when the before-mentioned simple red, green, and blue signal levels each directly correlated with a display colorant comprised of either red, green, and blue phosphors (CRT, Plasma), OLED pixels, or light valves plus color filters (LCD, DLP, LCOS) that produced the light. Due to this direct relationship of signal to light, through a straightforward electro-optical pathway, the methods of test could be greatly simplified and still produce accurate and efficacious results.

In contrast, modern display technologies are much more complex, and the methods used to produce and modulate light have diversified significantly. Examples are: LCDs with fluorescent backlights (both direct and edge-illuminated), LCDs with white LED backlights (in arrays or edge-illuminated), LCDs with RGB LED backlights, LCDs with LEDs and quantum dots, OLED displays, and micro-LED displays. New technologies are being developed and improved continuously. With these modern displays, it can no longer be assumed that there is a simple direct correlation between the input signal and the fundamental colorant of the display pixel. In fact, for some of these displays, red, green, and blue may be augmented with other fundamental colorants (e.g., white or yellow). Higher peak luminance levels may be achieved by the addition of white or some other fundamental colorant beyond the traditional R, G, B subpixels. Loss of additivity and reduced color volume can result. Modern digital signal processing provides pixel driving and color management. All of this is to demonstrate that, for example, sending a simple full-red signal to the black box may not only stimulate the red subpixel of the display. Additionally, the correlation of signal input to light output for each signal primary may not stay the same when the three signals mix at different ratios, often described as a lack of color additivity in the signal to light output response.

Display-Referred approach

The simple RGB component test signal used throughout the other IDMS chapters is not **Display-Referred**. Without context it has no definition as to the intended color output. This means that it has no defined dynamic range, it has no defined color space, it has no defined contrast ratio, and nothing prevents a display from responding to this signal with greater or lesser capability in these performance categories.



The key differentiating element of the HDR ecosystem is that the signal does have a clearly defined intent. The HDR content is mastered on a calibrated display with broad capabilities. The encoding of the signal describes the intent of the content creator, it describes what they intend the viewer to see. This **Display-Referred** signal forms the basis of the IDMS approach to HDR metrology.

For metrology purposes, this initial chapter focuses on HDR metrology and a single **Display-Referred** signal called the **IDMS HDR Test Signal**. This signal is assembled from two standards, SMPTE ST.2084 and ITU BT.2020. This **Display Referred Signal** describes exactly what is expected of the display. This signal standard is universally accepted on all currently available HDR displays. This signal includes static metadata describing the **Display-Referred** details such as the **EOTF** and a color gamut. This information is universally required by the **HDR DUT** to perform **Tone Mapping**. A common fixed set of metadata values provides a benchmark for metrology.

20.1.3 INTERDEPENDENCIES IN HDR METROLOGY

Modern displays have many variables that affect metrology. These may not be immediately obvious. The response of a DUT to a delivered signal may change over time. The contents of the test pattern itself may have a profound impact on the response to an individual signal value. Ever-increasing dynamic range increases the sensitivity to measurement geometry and setup conditions.

This section lists key variables that any HDR measurement method in this chapter must carefully control. These variables will influence the design of the test pattern, the setup conditions, the measurement procedures, and the reporting. Great care must be taken with respect to measurement methods using the **IDMS HDR Test Signal**. Often this complexity will result in methods that report sets of values to describe how the **Interdependencies** are interdependent.

Reported results should include all parameters that were controlled, and those that were not.

20.1.3.1 Test patch size, position, and shape

Many measurement methods utilize a test patch with an assigned uniform color value as part of a test pattern. The test patch is measured with an LMD according to the method. Such a test patch is commonly a rectangle with an aspect ratio equal to the screen. The measured color of a test patch can exhibit significant variation depending on the test patch size, location, and shape. Different geometric properties such as, a square, circle, or rectangle of different aspect ratio or size can directly affect measured results. Multiple measurements with different pattern sizes, shapes and on-screen locations may be required to properly evaluate an **HDR DUT**.

Considerations for patch size, shape, and position in the design of test patterns and methods for the **HDR DUT**:

- Real size of a patch relative to all display sizes
- Typical LMD apertures available and the relation to the absolute patch size
- Number of display pixels covered by available apertures
- Effects on power and driver system loading
- Effects of display protection systems
- Effects of backlight geometry relative to the size, shape, and aspect ratio of the test patch
- Effects of position relative to backlight geometry

20.1.3.2 Test pattern background

Many measurement methods utilize test patterns with test patches set against a black background. With modern display technology, variation of the background color may have a significant impact on the measured color of a test patch. A black background may not represent the response under typical usage as most images are more complex.



Measurement methods developed using the **IDMS HDR Test Signal** must anticipate the possible impact of the background in test pattern design. Multiple measurements with multiple pattern backgrounds may be the only way to properly evaluate a particular subject of metrological study.

Some considerations for test pattern background in the design of test patterns and methods for the **HDR DUT**:

- Effects on power and driver system loading
- Effects of display protection systems
- Effects of backlight geometry relative to the size, shape, and aspect ratio of the test patch
- Effects of the backlight control algorithm
- The pixel light modulation method

20.1.3.3 Spatial and temporal pixel dithering

Display systems of any technology may purposely add noise or patterns to ‘dither’ pixel data of flat color fields such as those typically found in test patterns. Such dithering can change the measured response of the system. Dithering can affect: apparent quantization of color in the temporal or spatial domain, apparent resolution, inter-frame detail, and the rate of angular color change. Dithering may benefit one measure at the detriment of another.

20.1.3.4 Temporal considerations

Typical IDMS methods suggest LMD measurement periods should be based simply on exposure and optimizing the signal to noise ratio of the measurement. The response of modern display systems to an **IDMS HDR Test Signal** value over time may vary.

Measurement method designs developed using the **IDMS HDR Test Signal** should anticipate the possible impact of multi-frame temporal changes. Synchronized, multiple measurements in different temporal frames may be the only way to properly evaluate a particular subject of metrological study.

Some temporal considerations for method design and LMD measurement of the **HDR DUT**:

- The period of one LMD measurement
- The number of LMD measurements in the sample period
- The integration of measurements over the sample period
- The length of the sample periods
- Expected signal to noise ratio for a given patch over one LMD measurement
- The **HDR DUT** response rate to the **IDMS HDR Test Signal** (rise and fall times)
- The ability of the **HDR DUT** to sustain the response to the **IDMS HDR Test Signal**

20.1.4 MASTERING DISPLAY METADATA (MDM)

A required element of the HDR signal standard (ST 2086) used by the **IDMS HDR Test Signal** is the Mastering Display Metadata (MDM). The MDM may have a profound effect on some metrology methods. The MDM provides contextual information to the **HDR DUT** about the display used by the content creator to view the content during final color grading (mastering). This information includes the color space and the luminance capability of the mastering display.

The color system used by the **IDMS HDR Test Signal** encodes a **Theoretical Display** with color capability that real-world displays may not be able to achieve (BT.2020, 0-10,000 cd/m²). By providing context with the MDM a display may, in some operational modes, better provide a perceptual **Tone Mapping** of the signal content to the display's color capability.

It is important to understand that all colors in the signal are valid for metrology. Code values outside the MDM are both allowed and in fact, common. Unfortunately, the standards that define and require the MDM do not in any way specify how the display should respond to this information. In current industry implementations, the behavior in response to the MDM is wildly different. Some displays have modes that provide a simple “colorimetric” match to the input signal. These colorimetric display modes may ignore the MDM and simply clip colors outside the display’s color capability. Such colorimetric modes would be optimal for display metrology, they may not be available on all displays. Other modes may



attempt to map color space such that the MDM color space is fit to the display. What happens to colors outside of the MDM is variable and unknown.

In this initial chapter on HDR metrology, careful consideration has been applied to reduce the number of variables to allow for consistency and reproducibility. One of those considerations was the decision to limit the MDM of the **IDMS HDR Test Signal** to a single set of parameters. Multiple signal parameters would multiply the work and reporting of every method by the number of permutations. Even a simple set of common MDM values (3 for luminance and 3 for chromaticity) would create 9 signal setups for each method.

It may initially seem obvious for metrology purposes to set the MDM parameters to match the full color capability of the encoded signal. However, many display systems will then compress the full signal within the range of the display resulting in large colorimetric error and unpredictable results to the test methods. The current choice of MDM by the ICDM is a reasonable compromise and fits the MDM used to master a great deal of current content. In the future, after additional study and maturation of the HDR ecosystem, the IDMS will likely provide further guidance on the MDM.

The metrologist is advised that choosing a mode (if available) that ignores the MDM is the best practice for HDR metrology at this time.

20.1.5 THE IDMS HDR TEST SIGNAL FORMAT

By defining a single **IDMS HDR Test Signal** that is clearly specified and unambiguous, many possible sources of confusion have been removed. This signal is directly derived from standards, however, those standards have been combined, and values for variables that those standards allow have been fixed. The HDMI signal format CTA 861.3^[4] allows many parameter formats to be utilized. The **IDMS HDR Test Signal** uses only one of two options from ITU-R Rec. BT.2100^[2] that is readily available on all display systems.

The **IDMS HDR Test Signal** might be referred to as an HDR10 implementation. The expression HDR10 has been adopted by the display industry to describe a signal that uses the **PQ** method from ITU-R Rec. BT.2100^[5] and **HDR Static Metadata** defined in ST 2086^[5]. In an actual application, HDR10 utilizes only 10-bit quantization but this limitation is not applied to the **IDMS HDR Test Signal**.

The use of a single test signal enables controls for the many variables the test signal itself can introduce into the measured results. Accuracy, consistency, and reproducibility are the foundation of proper metrology. The broader HDR ecosystem has many methods of signal delivery. By using a single standard test signal, reproducibility in HDR metrology is enabled. A metrologist may perform testing with other signals, however, only results that use the **IDMS HDR Test Signal** may reference the IDMS.

20.1.5.1 Parameter formats

The **IDMS HDR test signal** begins with defining the format of the parameter format being delivered. The parameter format has the following signal identification metadata: Component RGB Color Value, **PQ EOTF**, ITU-R Rec. BT.2020^[5] system colorimetry, Signal Range (Narrow or Full).

20.1.5.2 HDR static metadata

The HDR10 format includes basic **HDR Static Metadata** describing properties of the mastering display such as maximum mastering display luminance, minimum mastering display luminance, mastering display color primaries, as well as optional parameters such as 'MaxCLL' and 'MaxFALL'. The metadata may affect how the **HDR DUT** carries out functions such as **Tone Mapping**, and therefore, it may influence the measurement results. Details must be known so that the test can be reproduced without ambiguity. A common fixed set of metadata values provides a benchmark for metrology.

20.1.5.3 Transmission format

Recommended uncompressed format

Test patterns made from uncompressed individual frames will be provided for each measurement method as lossless 16-bit TIFF sequences. The **IDMS HDR Test Signal** is then generated from the TIFF files by adding a set of required metadata. The **IDMS HDR Test Signal** is then played out directly.



CTA 861.3 - AVI InfoFrame^[4]

Color System:	RGB
Quantization Range:	Full Range
Chromaticities:	BT.2020 ^[3]

CTA 861.3 - Dynamic Range and Mastering InfoFrame^[4]

EOTF:	PQ - SMPTE ST 2084 ^[5]
Mastering Display Primaries:	DCI-P3 ^[3]
Mastering Display White Point:	D65
Maximum Display Mastering Luminance:	4,000 cd/m ²
Minimum Display Mastering Luminance:	0 cd/m ²
Maximum Content Light Level:	0 (No Data)
Maximum Frame Average Light Level:	0 (No Data)

Alternative Delivery Compressed Format

This is a lossy compressed video format that will allow test patterns to be delivered using common consumer playback devices such as external media players. The nature of this format reduces the absolute precision and total quantization of the recommended format. Critical metrology should always use the recommended uncompressed delivery format. All test patterns will alternatively be provided as 10-bit quantized compressed high-efficiency video coding (HEVC) files to facilitate testing using common HDR playback systems. These will be encoded in the HEVC format from the uncompressed TIFF version. The **IDMS HDR Test Signal** derived from the HEVC file shall result in the following HDMI output format:

CTA 861.3 - AVI infoframe^[4]

Color System:	$Y' C'_B C'_R$
Quantization Range:	Narrow Range
Chromaticities:	BT.2020 ^[3]

CTA 861.3 - Dynamic range and mastering infoframe^[4]

EOTF:	PQ - SMPTE ST 2084 ^[5]
Mastering Display Primaries:	DCI-P3 ^[3]
Mastering Display White Point:	D65
Maximum Display Mastering Luminance:	4,000 cd m ⁻²
Minimum Display Mastering Luminance:	0 cd m ⁻²
Maximum Content Light Level:	0 (No Data)
Maximum Frame Average Light Level:	0 (No Data)

This second format has been defined for non-critical measurements and for compatibility testing with playback devices. See the sections on Quantization Range 20.1.5.5 and Color System 20.1.5.4 for more information. Both of these formats can be used to create static or motion test patterns.

20.1.5.4 Color system

The alternative delivery compressed format differs by color system. RGB delivery of the signal is preferred. The methods will utilize and specify RGB values in their descriptions. The $Y' C'_B C'_R$ format is provided because of limitations in supported implementations of the HEVC encoding format. Rounding errors that must be accounted for occur when RGB signals are converted to $Y' C'_B C'_R$; see details in the section below on HEVC encoding.

20.1.5.5 Quantization range

The alternative delivery compressed format differs by quantization range. In digital encoding, values are quantized to integers in an n -bit system. As some formats specify certain signal values that are reserved and cannot be used to describe colors or intensities, a start and end point for valid colors must also be described. ITU-R Rec.BT.2100^[2] describes two quantization encoding ranges for HDR signals: Full Range and Narrow Range (see Table 1).

Full Range, from 0 through $2^n - 1$, (where n is the bit-depth of the integer encoding), is commonly used with computer displays and other IDMS test signals. As such, code values in **IDMS HDR Test Signal** patterns are defined using full-range quantization.



Narrow Range provides headroom above and below the maximum and minimum encoding levels (e.g. 8-bit 16 through 235, 10-bit 64 through 940). Please refer to the HDR tutorial B33 for more information.

Table 1. Digital 10- and 12-bit integer representation; quoted from Table 9 of ITU-R Rec.BT.2100^[2].

Parameters	Values			
Coded signal	R', G', B' or $Y' C'_B C'_R$ or $I C_T C_P$			
Coding format	$n = 10, 12$ bits per component			
Quantization of R', G', B', I' (Resulting values that exceed the video data range should be clipped to the video data range)	Narrow range $D = \text{Round}[(219 \times E' + 16) \times 2^{n-8}]$		Full range $D = \text{Round}[(2^n - 1) \times E']$	
Quantization of C'_B, C'_R, C_T, C_P (Resulting values that exceed the video data range should be clipped to the video data range)	$D = \text{Round}[(224 \times E' + 128) \times 2^{n-8}]$		$D = \text{Round}[(2^n - 1) \times E' + 2^{n-1}]$	
Quantization levels	10-bit coding	12-bit coding	10-bit coding	12-bit coding
Black ($R' = G' = B' = Y' = I = 0$) DR', DB', DB', DY', DI	64	256	0	0
Nominal peak ($R' = G' = B' = Y' = I = 1$) DR', DB', DB', DY', DI	940	3760	1023	4095
Achromatic ($C'_B = C'_R = 0$) DC'_B, DC'_R, DC_T, DC_P	512	2048	512	2048
Nominal peak ($C'_B = C'_R = +0.5$) DC'_B, DC'_R, DC_T, DC_P	960	3840	1023	4095
Nominal peak ($C'_B = C'_R = -0.5$) DC'_B, DC'_R, DC_T, DC_P	64	256	1	1
Video data range	4 through 1019	16 through 4079	0 through 1023	0 through 4095

'HDR10' signals are encoded with 10 bits per component precision, in order to avoid potential contouring or 'banding' artifacts that otherwise can appear in gradients with a lower bit depth encoding. A quantization of 10 bits is rarely needed for metrology test patterns. Therefore, all methods have been developed such that 8-bit precision is sufficient unless otherwise specified.

Although Full Range signals are used in the **IDMS HDR Test Signal** patterns, quantization range conversions of such Full Range signals *will* inevitably result in rounding errors; the math used in the conversions results in a fractional value which must be rounded (or truncated) to the nearest integer value.

20.1.5.6 HDR metrology and HEVC encoding

The alternative delivery compressed format was necessitated to solve an issue with the cost of motion test signal delivery. For sophisticated signal generators or high-speed computers capable of delivering motion video from individual lossless TIFF frames this is not an issue, and this format should not be used.

To make the motion test signals widely available to metrologists, it was decided to also utilize the HEVC video format. However, industry implementations of HEVC decoding provide some challenges.



Although HEVC allows encoding of non-subsampled (4:4:4) signals, and therefore RGB, the HEVC Main 10 profile used in current video products is limited in that it only supports $Y'C'_B'C'_R$ 4:2:0 as the format for encoding. The use of HEVC for motion test signals therefore requires conversion of the color system from RGB to $Y'C'_B'C'_R$. Additionally, a conversion of the quantization range from Full to Narrow is required. Both of these operations *will* inevitably result in rounding errors; the math used in the conversions results in a fractional value which must be rounded (or truncated) to the nearest integer value. ITU-R Rec.BT.2100^[2] defines the derivation of the $Y'C'_B'C'_R$ signal format (see Table 2).

Table 2. Non-constant luminance $Y'C'_B'C'_R$ signal format; quoted from reference ITU-R Rec.BT.2100^[2], table 6

Parameter	PQ values
Derivation of R', G', B'	$\{R', G', B'\} = \text{EOTF}^{-1}(F_D)$, where $F_D = \{R_D, G_D, B_D\}$
Derivation of Y'	$Y' = 0.2627R' + 0.6780G' + 0.0593B'$
Derivation of colour difference signals	$C'_B = \frac{B' - Y'}{1.8814}, C'_R = \frac{R' - Y'}{1.4746}$

Any test pattern decoding the alternate delivery compressed format should be configured to output $Y'C'_B'C'_R$, even capable of outputting RGB to avoid any possibility of an additional conversion rounding error.

Great care should be taken by the metrologist to ensure that a) the test equipment source truly is outputting the expected signal without unexpected conversions, b) the display is configured or interpreting the signal correctly, and c) the rounding errors from conversion must be accounted for in the interpretation of the measurement results. Methods that describe the use of motion video files shall provide procedures to account for the rounding error.

As examples, Table 3 and Table 4 show the luminance levels resulting from 8, 10, and 12-bit grey triplets for Narrow and Full range, respectively, which have been calculated using the **PQ EOTF** in Equation (1) and (2). Whenever test signals and measurement procedures are described, the necessary code values should be reported accordingly.

Table 3. Calculated Narrow Range **PQ EOTF** for 8, 10, and 12-bit coding. The quantization level is the input signal to the **PQ EOTF** and is defined for all signal components ($R' = G' = B' = Y' = I$).

Quantization level	8-bit coding	Luminance (cd/m ²)	10-bit coding	Luminance (cd/m ²)	12-bit coding	Luminance (cd/m ²)
0	16	0.00	64	0.00	256	0.00
0.005	19	0.00	77	0.00	309	0.01
0.01	21	0.01	83	0.01	331	0.01
0.1	30	0.11	119	0.10	474	0.10
1	49	1.01	195	0.99	781	1.00
10	82	10.21	327	10.07	1306	9.99
100	127	98.78	509	99.91	2036	99.91
200	143	201.49	571	199.30	2285	199.85
300	152	297.59	609	300.80	2435	299.99
400	159	401.45	636	401.45	2543	400.39
500	164	496.37	657	501.65	2627	500.33
600	168	587.77	674	600.29	2696	600.29
700	172	695.61	689	702.96	2754	699.28
800	175	789.06	701	797.38	2805	799.48
900	178	894.89	713	904.32	2850	899.59
1000	181	1014.76	723	1004.19	2890	998.95



2000	197	1982.80	789	2003.69	3155	1998.45
4000	214	4057.49	855	4014.72	3419	4004.10
10000	235	10000.00	940	10000.00	3760	10000.00

Table 4. Calculated Full Range PQ EOTF for 8, 10, and 12-bit coding. The quantization level is the input signal to the PQ EOTF and is defined for all signal components ($R' = G' = B' = Y' = I$).

Quantization level	8-bit coding	Luminance (cd/m ²)	10-bit coding	Luminance (cd/m ²)	12-bit coding	Luminance (cd/m ²)
0	0	0.00	0	0.00	0	0.00
0.005	4	0.01	15	0.00	62	0.01
0.01	5	0.01	22	0.01	88	0.01
0.1	16	0.10	64	0.10	255	0.10
1	38	0.98	153	0.99	614	1.00
10	76	9.79	307	10.05	1227	9.99
100	130	101.73	520	100.23	2081	100.10
200	148	202.42	592	199.15	2372	200.21
300	159	304.74	636	299.54	2547	300.33
400	166	394.08	668	401.51	2672	399.72
500	173	508.63	692	499.34	2771	500.44
600	178	609.74	712	598.33	2851	599.56
700	182	704.62	729	697.41	2920	700.34
800	186	813.99	744	798.15	2979	799.61
900	189	906.89	757	896.98	3032	900.57
1000	192	1010.27	769	998.93	3079	1000.60
2000	211	2000.48	846	1991.84	3388	1998.64
4000	230	3977.36	923	3987.98	3696	3999.69
10000	255	10000.00	1023	10000.00	4095	10000.00

20.1.5.7 Colorimetry

ITU-R Rec.BT.2100^[2] defines a set of primaries to be used for HDR signal encoding. The color space is very large as it consists of monochromatic wavelength primaries (see Table 5).

Table 5. Reference primaries; quoted from ITU-R Rec.BT.2100^[2]; table 2.

Parameter		Values		
		Optical spectrum (informative)	Chromaticity coordinates (CIE, 1931)	
			<i>x</i>	<i>y</i>
Primary colours	Red primary (R)	monochromatic 630 nm	0.708	0.292
	Green primary (G)	monochromatic 532 nm	0.170	0.797
	Blue primary (B)	monochromatic 467 nm	0.131	0.046
Reference white		D65 per ISO 11664-2:2007	0.3127	0.3290
Colour matching functions		CIE 1931		



20.1.5.8 EOTF

The **Perceptual Quantizer (PQ) EOTF** defined in SMPTE ST 2084^[5] provides a key component of the **Display-Referred IDMS HDR Test Signal**. It encodes the luminance steps modelled after perceptual detectability thresholds. It therefore provides efficient quantization distribution of luminance information and mitigates (10 bits) or eliminates (12 bits) contouring artifacts. For more information see the HDR tutorial B33. The **PQ EOTF** system reference non-linear transfer functions are provided in ITU-R Rec.BT.2100^[2] table 4:

$$F_D = \text{EOTF}[E'] = 10000Y \quad (1)$$

and

$$Y = \left(\frac{\max[(E'^{1/m_2} - c_1), 0]}{c_2 - c_3 E'^{1/m_2}} \right)^{1/m_1} \quad (2)$$

where:

E' denotes a non-linear colour value $\{R', G', B'\}$ or $\{L', M', S'\}$ in **PQ** space in the range $[0: 1]$

F_D is the luminance of a displayed linear component $\{R_D, G_D, B_D\}$ or Y_D or I_D in cd/m^2

So that when $R' = G' = B'$, the displayed pixel is achromatic.

Y denotes the normalized linear colour value, in the range $[0: 1]$

$$m_1 = \frac{2610}{16384} = 0.1593017578125$$

$$m_2 = \frac{2523}{4096} \times 128 = 78.84375$$

$$c_1 = \frac{3424}{4096} = 0.8359375 = c_3 - c_2 + 1$$

$$c_2 = \frac{2413}{4096} \times 32 = 18.8515625$$

$$c_3 = \frac{2392}{4096} \times 32 = 18.6875$$

20.1.6 HDR Performance and Reporting

The ICDM does not set performance thresholds for methods; performance thresholds are outside the scope of this organization.

Methods utilizing the **IDMS HDR Test Signal** are designed for comparison purposes. They are unbiased and aim to describe aspects of displays independent of technology. These methods should require the reporting of **Interdependencies** that may affect the method.

All IDMS measurement methods, including those utilizing the **IDMS HDR Test Signal**, contain specific reporting requirements. When referencing IDMS methods and reporting results from IDMS methods, all aspects of required reporting in any context should be followed. Additional analysis or calculated values that are not contained in the official reporting section should not reference the IDMS.

20.1.7 References

- [1] ITU-R Recommendation BT.2020-2 (10/2015), "[Parameter values for ultra-high definition television systems for production and international programme exchange](#)": Primary color coordinates used in the **IDMS HDR Test Signal**
- [2] ITU-R Recommendation BT.2100-2 (07/2018), "[Image parameter values for high dynamic range television for use in production and international programme exchange](#)": Used to define the **IDMS HDR Test Signal EOTF**
- [3] SMPTE ST 431-1:2006, "[D-Cinema Quality – Screen Luminance Level, Chromaticity and Uniformity](#)" (DCI-P3), DOI: [10.5594/SMPTE.ST431-1.2006](#). Common color gamut used for content mastering. The consumer versions with D65 white point is derived from this standard.
- [4] Consumer Technology Association CTA-861.3 (January 2015), "[HDR Static Metadata Extensions](#)": Defines the structure of the **IDMS HDR Test Signal** over HDMI.
- [5] SMPTE ST 2084:2014, "High Dynamic Range Electro-Optical Transfer Function of Mastering Reference Displays", DOI: [10.5594/SMPTE.ST2084.2014](#). Used to define the **EOTF** of the **IDMS HDR Test Signal**.
- [6] SMPTE ST 2086:2018, "Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images.", DOI: [10.5594/SMPTE.ST2086.2018](#). Used to define the **IDMS HDR Test Signal** and **HDR Static Metadata**.



21. COLOR FOR DISPLAY METROLOGY

Many new display technologies have been developed since IDMS version 1.03b was released so there is a need for updating the characterization of color displays. Certain conventional metrics are no longer adequate for describing the characteristics of color displays.

The purpose of this chapter is to provide the reader with the necessary understanding of colorimetry to make proper display color measurements on displays that make their own light in a dark room condition, *i.e.*, excluding reflective displays. This chapter provides tutorials on metrology for color displays. The reader can refer to this chapter to obtain a basic idea of color measurements, which are performed in several kinds of display measurements. Compound metrics for color measurements that are supplementary to photometry or other parameters are excluded from this chapter, including color gamut volume, the measurement of which is provided in 5.32. In this chapter, we limit ourselves to standard dynamic range, in which diffuse white is unambiguously defined through normalization of the tristimulus values to the peak white luminance level. Subjective evaluations, such as color preferences, memory colors, and image quality are beyond the scope of this chapter because they cannot be deduced from colorimetry alone. The basic ideas and equations of the Commission Internationale de l'Éclairage (CIE) standard colorimetries are provided in appendix B1. This tutorial section rather discusses the CIE standards and non-standard metrics from the viewpoint of display color metrology.

21.1. Metrology and Color Displays

The IDMS covers metrology or the science of measurements for displays. Although the ICDM is continuously revising the IDMS measurement methods and metrics, it never means proliferating inconsistent metrics, rather the very opposite. Metrology for color displays, including evaluation methods based on the resulting measurements, should be technologically neutral and independent of architecture. The scope of the ICDM is restricted to displays with RGB-encoding and therefore the metrology is input referred. Most input signals are tri-chromatic and based on additive color mixing of the three primary colors red, green, and blue (RGB). The chromaticity coordinates of the RGB primaries are standardized in each signal encoding, and any input signals are assumed to be based on one of the standardized tri-chromatic system chromaticities.

The RGB optical color channels of displays are often referred to as “display primaries.” The chromaticity coordinates of those RGB optical color channels are, however, not necessarily identical to those of the standard RGB assumed by the input signal carrying the encoded image content. No color space shall be assumed in color display metrology, that is, the measurement is unbound. What is measured is simply the optical response to a dimensionless input signal. Furthermore, displays with extra optical color channels such as cyan, magenta, and yellow (CMY) and/or white (W) are sometimes referred to as “multi-primary” displays. From the perspective of input-referred metrology, the primaries are defined by the input signals, which are RGB. The term “tri-chromatic primaries” is defined as three light sources specified additively so that no one of them equals any mixture of the other two, that is, they are orthogonal. In tri-chromatic displays, nobody would intentionally make them with one channel dependent on the other two, so pragmatically they are all three-primary displays. It is therefore confusing to define the extra color channels (with any combination of CMY secondary colors and/or W) as “primaries” unless there is also such an additional input signal (e.g., output from a multi-spectral imaging camera). Since the common input denominator for all displays is RGB, the term “multichromatic” [21.1] is more appropriate than “multi-primary” when referring to displays with more than the three conventional RGB optical color channels, including configurations such as RGBW, RGBCMY, and RGBY. The term is analogous to the way black-and-white displays or, *e.g.*, green-only phosphor displays are referred to as monochrome. Thus, RGB displays are tri-chromatic, and RGB plus any additional color channels are multichromatic, regardless of the dependency of the additional chromatic channels on the RGB primaries.



21.2. Colorimetry

The science and technology of measuring color is called colorimetry. The basic standards for colorimetry are developed by the CIE, which has been recognized by the International Organization for Standardization (ISO) as an international standardizing body. In 1931, the CIE published its first major recommendations for colorimetry. Since then, new CIE colorimetry editions have been published from time to time to make changes and add new recommendations. The latest edition, CIE 015:2018 Colorimetry 4th Edition, was published in 2018 [21.2]. The most fundamental tables and formulae in CIE 015 were also published as joint ISO/CIE standards, known as the Colorimetry Series.

The development of colorimetry can be divided into three stages: color specification, color difference and color appearance [21.3]. The CIE tristimulus values are for color specification. If two colors have the same tristimulus values, those two colors will look the same to the CIE standard observer. However, the tristimulus values neither explain the color appearance such as lightness, chroma or hue, nor the size of color difference between two stimuli. To measure the color difference between two stimuli, two color appearance formulae based on CIELAB and CIELUV uniform color spaces were recommended by the CIE in 1976, which has been further developed as the CIE ΔE_{2000} color difference formula. To accommodate differences in color appearance by different viewing conditions, a color appearance model is needed. CIECAM16 is the latest color appearance model developed by the CIE.

Even though the limitations of CIELAB, CIELUV, and ΔE_{2000} are well understood, they remain the internationally standardized metrics for color measurement. Thus, all the color measurement data in the IDMS are expressed in terms of the CIE colorimetric values. A challenge, however, is the ambiguity in selecting the type of chromaticity diagram, color space, or color difference equations for measuring color displays. In the following subsections, the CIE recommendations are explained from the perspective of display color metrology.

21.2.1 Tristimulus Values and Standard Colorimetric Observer

The color specification in the CIE Colorimetry is based on color matching. It is well known that various colors can be generated by mixing red, green, and blue lights. Therefore, the amount of three lights matching the appearance of color stimulus can be used to quantify color. Based on this concept, the International Lighting Vocabulary (CIE S 017/E:2011) defines color stimulus in terms of tristimulus values, which are the amounts of the three reference color stimuli in a given trichromatic color vision system required to match the color of the stimulus considered [21.4], [21.5].

The CIE colorimetric system is based on color-matching functions, *i.e.*, results of color matching between monochromatic stimuli and the reference RGB stimuli. The color-matching experimental result shows that some monochromatic lights cannot be matched using any given set of RGB lights. For example, 500 nm monochromatic light cannot be matched using 700.0 nm, 546.1 nm, and 435.8 nm RGB lights. Instead, the 500 nm light plus red can be matched with a green and blue mixture. Such a phenomenon generates negative tristimulus values which lack physical meaning (light energy cannot be negative). To avoid the negative values and link colorimetry to photometry, the CIE RGB system was transformed to the CIE XYZ system by linear combinations.

There are three CIE colorimetric systems – the CIE 1931 standard colorimetric system, CIE 1964 standard colorimetric system and CIE 2015 cone-fundamental-based colorimetry. For visual color matching of fields of view (FOV) subtending between about 1° and about 4° at the eye of the observer, the CIE 1931 standard colorimetric system determines the tristimulus values of any spectral power distribution (SPD) using the color-matching functions known as the CIE 1931 standard colorimetric observer (the 2° standard colorimetric observer). For visual color matching of FOVs larger than 4°, colorimetric specifications of color stimuli should be based on the color-matching functions defined as the CIE 1964 standard colorimetric observer (the 10° standard colorimetric observer). In 2015, the CIE published CIE 170-2:2015 [21.6] introducing a new set of color-matching functions based on cone-fundamental-based tristimulus functions which use the age of the observer and the FOV as parameters.

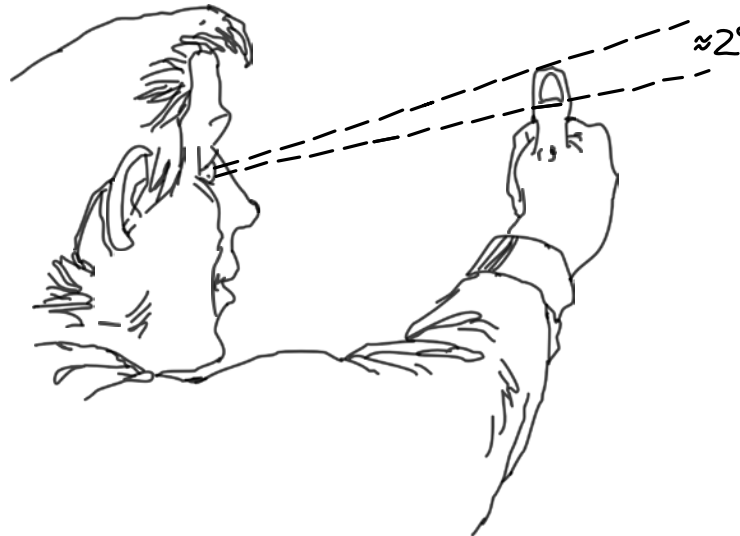


FIGURE 21.1. A rule of thumb is that the width of the thumbnail – when the arm is extended – is about 2°

The ICDM currently recommends the use of the CIE 1931 2° color-matching functions for measuring color displays. The XYZ tristimulus values for a stimulus are obtained by multiplying the CIE 1931 color-matching functions by the SPD and integrating across the spectrum, (see appendix B1.2). The 2° color-matching functions are chosen because they represent a typical use case of a display, where the content will be observed within a rather small angle, for example, details on a photograph or artwork. When a display shows large content blocks, the 10° observer might be better suited but since it is difficult to predict the displayed content and field of view, it makes sense to standardize on the 2° observer for display measurements. The next section will explain why we still use the CIE 1931 colorimetry.

21.2.2 Observer Metamerism

Observer metamerism refers to situations where a pair of visual stimuli produce a colorimetric match for one observer, but do not match for another observer. The mismatch occurs due to differences in the two observers' spectral sensitivities. An "observer" could refer to an observer such as the CIE 170-2:2015 [21.6] parametrized color-matching functions, a measurement device, or an individual person. The effects of observer metamerism tend to be larger for stimuli that have narrow SPDs in the visible spectrum. As tri-chromatic wide-gamut displays, which achieve highly saturated colors using spectrally narrow-band optical color channels, have grown more common, observer metamerism has become more relevant in the display industry [21.7].

Research on this topic by the CIE and throughout the display industry is ongoing. This includes quantifying the amount of variation in spectral sensitivity throughout the population, modelling significant causes of variation by the parametric color-matching functions [21.6], and creating improved standard observer functions that better represent the average person. The ICDM does not currently recommend any specific procedures or measurements relating to observer metamerism because reliable methods of quantifying and correcting it have not yet been standardized. Color errors caused by differences between a standard observer used for display calibration and a human observer are usually only noticeable for colors other than white and memory colors, when the adaptation is incomplete, or when viewing two displays side-by-side that have color primaries with different SPDs. Therefore, any colorimetry in this guideline is based on the CIE 1931 2° color-matching functions; observer metamerism failure is currently not considered for measuring color displays.

21.2.3 Chromaticity Diagrams

In cartography, a world map is a projection of the features of the globe onto a 2D plane. Since the flattening of a spherical surface always causes distortions in areas, directions, distances, and the shapes of the features, various projection methods have been used. Mapping of a 3D color space is like a map projection of the globe; we need to

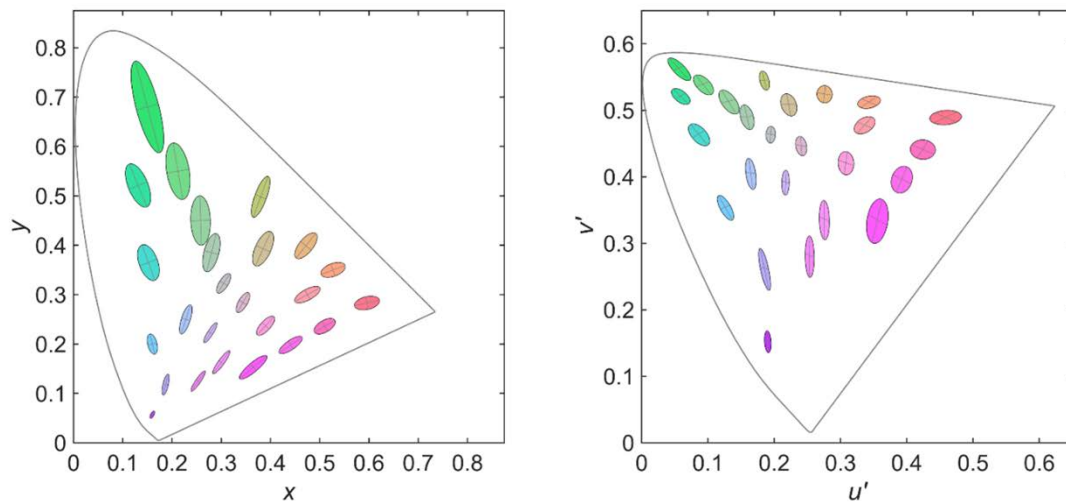


FIGURE 21.2. MacAdam ellipses in CIE 1931 xy (left) and CIE 1976 $u'v'$ (right) chromaticity diagrams. Axes of plotted ellipses are 10 times their actual lengths.

produce a map with a minimal distortion that is evenly weighted in terms of human perception in all the axes combined.

There are two maps or chromaticity diagrams that have been standardized by the CIE: xy and $u'v'$. (Although each diagram is a chromaticity “space,” a two-dimensional space is often referred to as a “diagram” in color science.) Both these diagrams are used to visualize the chromaticity coordinates of the white point, the standard RGB primaries, and/or additional optical color channels. The CIE 1931 xy chromaticity diagram is often used because x , y , and z are simple normalizations of the three tristimulus values X , Y , and Z in the following manner:

$$x = \frac{X}{X + Y + Z} ; y = \frac{Y}{X + Y + Z} ; z = \frac{Z}{X + Y + Z} \quad (21.1)$$

Once normalized, we can define the chromaticity of a color with two of these components because $x + y + z = 1$. Thus, the 2D CIE 1931 xy diagram is a straightforward representation of basic colorimetry, albeit with distortions. The CIE 1976 $u'v'$ chromaticity diagram is an update that shows a more perceptually uniform chromaticity spacing. It is a projective transformation of the CIE 1931 xy diagram. Figure 21.2 shows the CIE 1931 xy and CIE 1976 $u'v'$ diagrams with MacAdam ellipses [21.8]. These contours approximately enclose just-noticeable difference (JND) areas in the xy and $u'v'$ diagrams. The sizes of the green ellipses and of the overall green area are exaggerated in the CIE 1931 xy diagram (much like Greenland appears to be larger than it is in the Mercator mapping projection). The ellipses in the $u'v'$ diagram are closer in size than those in the xy diagram, which suggests that the $u'v'$ diagram, though not perfect, is more perceptually uniform than the xy diagram. (If the diagram had perfect perceptual uniformity, all ellipses would be circles of the same size.) To judge tolerances of the RGB primaries and white points, Euclidean distances (Δxy and $\Delta u'v'$) are often measured on both these diagrams; in the xy diagram and in the $u'v'$ diagram for perceptual chromaticity uniformity. In the latter case, the nominal perceptual uniformity in the $u'v'$ diagram can be considered valid only when the luminance level of each color is the *same*. Perceptual differences in the $u'v'$ diagram depend on luminance, but that fact is not evident from the diagram. We must therefore be careful not to draw strong conclusions from the diagram [21.9]. Furthermore, MacAdam ellipses were basically measured from a *single* observer in a matching experiment, and not a discrimination experiment [21.10], and other experiments resulted in ellipses with different sizes and orientations [21.11]. While CIE ΔE_{2000} (see 21.2.6) significantly improves the perceptual uniformity, it is not perfect, but it is the best one that has been standardized so far and must therefore be used. Based on ΔE_{2000} calculations, the uniformity of $u'v'$ over xy is not proved around neutral colors [21.12].



21.2.4 Uniform Color Spaces

Many color spaces have been developed over the years for various applications. For measurement purposes we need a three-dimensional color space that is “perceptually uniform” (see Section 21.3.2 “Color Gamut is a Volume”). A volume is defined as the amount of space, measured in cubic units, that an object or substance occupies.

When measuring the volume of different substances, there may be confounding factors, such as temperature and pressure. If a physical substance is not all at the same temperature and pressure, the volumetric calculation may be in error. It is therefore important to make sure that the methods, procedures, and metrics take into account everything that can affect the measurement and make it work for all instances. For instance, the actual temperature and homogeneity of temperature throughout a gas would be very important for making a repeatable volumetric measurement.

To accurately measure volume in terms of the capabilities of human color perception, the color space we use must have the property of “perceptual homogeneity”, which means that it must be perceptually uniform not only in chromaticity, but in all three dimensions at all scales. A small unit distance in a dark region must be perceptually similar to the same unit distance in a much lighter region. A set of points displaced by the same unit distance vertically or diagonally must also have the same perceptual length. This must also be true of larger distances in all directions. A model that might be useful to describe small distances might fail at much larger ones.

The xy and u^*v^* chromaticity diagrams are not color spaces because they do not contain the luminance or lightness dimension. (Lightness is defined as the attribute of a visual sensation according to which an area appears to emit, transmit, or reflect more or less light compared to an area perceived as white.) Stevens’ power law is found in the relationship between CIE XYZ tristimulus values and the predictors of lightness and chroma. Often, the chromaticity diagrams are extended to three-dimensional (3D) spaces by adding a linear or log luminance dimension, such as Yxy and Yu^*v^* (the upper-case Y in this case denotes relative luminance, but it can also be used for absolute luminance) to show 3D color solids. Although these are now 3D color spaces, neither of them is perceptually uniform (see 21.3.4 “Chromaticity Gamut Area”).

The CIELAB color space published by the CIE in 1976 was designed as a perceptually uniform color space. It has three Cartesian coordinates axes, L^* , a^* and b^* . The lightness L^* is similar to the Munsell “Value” scale. The Munsell system was designed such that an intermediate gray is perceptually halfway between an ideal white and an ideal black as well as between any gray pairs under the consistent adaptation state to accommodate both macro (a large number of JNDs) and micro (as small as a single JND) color differences. The a^* and b^* axes roughly correspond to the opponent color signals, redness-greenness and yellowness-blueness, in the human visual system. A color can be represented in cylindrical coordinates as well in terms of CIELAB C^* : chroma, h : hue angle, and L^* : lightness. CIELAB has been well established for decades; it is well understood and is widely used in contracts, specifications, and device-independent color exchange. The International Color Consortium (ICC) uses it for device proofing [21.13], [21.14].

CIELUV, published by the CIE in 1976, is another color space but it is not used for volumetric measurement but rather, for example, in gamut mapping algorithms. In CIELUV, equal luminance RGB lights can be linearly combined at a constant L^* on the u^*v^* plane. (This is evident from the fact that the u^*v^* coordinates are precursors of the u^*v^* coordinates and are often easy to use when dealing with self-luminous colors.) For volume calculations, however, there is significant non-homogeneity that leads to uneven weighting of color ranges in different parts of the color space [21.15]. It is for this reason that the CIE recommended the use of CIELAB for volume calculations and not CIELUV [21.16]. The belief that CIELUV is better for expressing small differences and CIELAB for large ones may come from their derivation from MacAdam and Munsell respectively, but the CIE felt there was no basis to recommend this distinction since they had no data to support it [21.15]. Another occasional misconception is that one color space applies best to object (reflective) colors and the other to self-luminous colors, but there is no evidence to support this, and the CIE did not recommend this distinction either [21.15].

To enable a meaningful gamut volume metric, gamuts from different displays must be transformed to a single white point. Use of a single white point does not penalize displays that use a white point other than D50 [21.18]; rather,



the transformation enables meaningful comparisons based on the same chromatic adaptation. In section 21.3, color gamut volumes are shown in different 3D color spaces, indicating the importance of perceptual homogeneity of color space for volumetry. Volumetry in the D50 CIELAB color space is detailed in Section 5.32 Color Gamut Envelope – Color Capability. Subsection 5.32.1 provides an algorithm to compute CIELAB gamut volume. Nonlinear RGB input levels (R', G', B') are uniformly sampled from the faces of the cube-shaped RGB color-encoding space to determine the gamut boundary. Each RGB cube face is comprised of an 11×11 lattice, yielding a total of 602 $R'G'B'$ sets.

Additionally, the tessellation order is determined during the RGB sampling stage. The tristimulus values are calculated from the $R'G'B'$ values and transformed to the relative D50 tristimulus values using the Bradford chromatic adaptation transform. The relative (X, Y, Z) coordinates are converted to (L^*, a^*, b^*) coordinates. The metric conforms to the IEC 62977-2-1 method [21.17].

21.2.5 Color Appearance Model

Color is a characteristic of visual perception that can be described by the attributes hue, brightness (or lightness) and colorfulness (or saturation or chroma) [21.19]. The color appearance changes not only according to the spectral power distribution of the stimulus but is also affected by the size, shape, spatial structure and surround of the stimulus area. It also depends on the adaptation state of the observer and on other factors such as age and field of view. The same CIE XYZ values or CIE $L^*a^*b^*$ values do not guarantee the same color appearance unless the stimuli occur under the same viewing conditions. For example, a gray patch looks darker when shown on a white background compared to when the same patch is shown on a black background.

In 1997, the CIE recommended the color appearance model, CIECAM97s, for predicting the appearance of colors across a wide range of viewing conditions. It was superseded by CIECAM02 [21.20] in 2002, which rectifies some of the shortcomings of CIECAM97s. Though CIECAM02 has been widely accepted and performs well compared to other models, some additional inconsistencies and shortcomings were found. Within the CIE, the work of technical committees is still ongoing to include new findings and fix those shortcomings.

Currently, the IDMS does not recommend using CIECAM16 since it is not easy to define a single standard viewing condition for measuring displays. Also, the benefits of using this color appearance model for display metrology are not fully agreed. Further investigation is needed for the IDMS to adopt CIECAM16.

21.2.6 Color Difference Equations

Since the CIELAB space is approximately uniform and homogeneous, the Euclidean distance (ΔE_{ab}^*) between two points equals the color difference between them. By contrast, CIELUV uses a subtractive shift in the chromaticity coordinates, ($u' - u'_n, v' - v'_n$), instead of the multiplicative normalization of the tristimulus values ($XX_n^{-1}, YY_n^{-1}, ZZ_n^{-1}$) incorporated in CIELAB. Here, u'_n and v'_n are the chromaticity coordinates of the reference white with tristimulus values X_n, Y_n, Z_n . The intrinsically flawed subtractive adaptation transform can yield negative tristimulus values and is extremely inaccurate with respect to predicting visual data [21.10]. Therefore, the CIELAB color space should be used for color difference calculation instead. Nonetheless, the CIE recognized some non-uniformities of the CIELAB color space, and therefore formulated a more advanced color difference equation, CIE ΔE_{2000} . Its equations are more complex due to abandoning Euclidean color space. The CIE recommends using the ΔE_{2000} equation instead of the simple Euclidean distance calculation in CIELAB or CIELUV for calculating color differences, yet all of them are still standardized by the ISO/CIE.

In 2019, the International Telecommunication Union (ITU) standardized ΔE_{ITP} (formerly $\Delta IC_t C_p$) as an objective color difference metric in Rec. ITU-R BT.2124 for assessing the potential visibility of small color differences in television images [21.21], [21.22]. ΔE_{ITP} is based on the $\Delta IC_t C_p$ color representation standardized in Rec. ITU-R BT.2100. Volumetry in the $IC_t C_p$ space [21.23] is not meaningful in terms of color appearance for large color differences, *e.g.*, perceptual lengths, but it can be used to assess the magnitude of local color differences that might impact content display over a large luminance range offered with HDR imaging and display.



Note that metrology in the context of HDR imaging is still an active area of research and academic discussion. For more information about HDR and PQ in particular, please refer to the HDR Chapter 20 and the HDR tutorial B33 in the appendix.

21.3. Display Color Gamut

The chromaticities for ultra-high-definition television were standardized in 2012 in Rec. ITU-R BT.2020 (Rec. 2020) [21.24]. The Rec. 2020 RGB primary set was designed to encompass major standard color spaces, including Rec. ITU-R BT.709 (Rec. 709) for high-definition television (HDTV) [21.25], Digital Cinema Initiatives (DCI)-P3 for digital cinema [21.26], Adobe RGB for the de facto standard in professional color processing [21.27], and most object colors [21.28]. Presently, many consumer displays are compatible with the Rec. 2020 color representation but, importantly, their inherent gamut sizes vary and are generally smaller than that of Rec. 2020. Such displays can apply color transformations to the RGB input signals to correct their chromaticities for specific display devices, and they are capable of at least partially producing the Rec. 2020 gamut. Many so-called “wide-gamut” displays are using the Rec. 2020 container, even though they cannot achieve overlap with the Rec. 2020 color gamut, or not even the Rec. 2020 chromaticity area. Consequently, measurement of the color gamut is important.

21.3.1 Standard RGB Primaries

In this document, the distinction is made between the “device gamut” and the “usable gamut.” The device gamut is the range of colors reproduced by all possible combinations of unbound digital input signals. Unbound means that there is neither any host-side color management, nor any handshaking taking place between the host and the device. The usable gamut is, on the other hand, a subset of the device gamut and tied to the standard color encoding of the input signal.

Nearly all standard color encodings assume additivity and are trichromatic with RGB primaries, the chromaticities of which are generally defined by their xy coordinates. Image color can also be encoded by luma and chroma (YC_aC_b), but this is not relevant in display metrology since the test patterns are defined by RGB. TABLE 21.1 shows the xy chromaticity coordinates of the Rec. 709, DCI-P3, Adobe RGB and Rec. 2020 primaries. The primaries are often visualized as a triangle formed by connecting the chromaticity coordinates (RGB triangle) in the xy or $u'v'$ chromaticity diagram for each standard. The chromaticity coordinates of the Adobe RGB and DCI-P3 blue primaries are identical to those of the Rec. 709 blue primary. The chromaticity coordinates of the Adobe RGB red and green primaries are identical to the Rec. 709 red primary and the obsolete National Television System Committee (NTSC) 1953 green primary, respectively [21.29]. FIGURE 21.3 shows the RGB triangles of Rec. 709, DCI-P3, Adobe RGB and Rec. 2020 in the xy chromaticity diagram. The area of an RGB triangle reflects the range of reproducible chromaticities by the trichromatic system based on Grassmann’s laws of additive color mixture.

Linear RGB values, which are obtained by nonlinear decoding of the nonlinearly encoded signal, can be converted to tristimulus values using a 3×3 matrix based on the chromaticity coordinates of the RGB primaries and the white point. Nonlinearly encoded values are denoted with primes as $R'G'B'$, although the primes are confusingly often omitted. For example, the equations for Rec. 2020 and Rec. 709 are as follows (RGB values are normalized to unity):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.6369580 & 0.1446169 & 0.1688810 \\ 0.2627002 & 0.6779981 & 0.0593017 \\ 0 & 0.0280727 & 1.0609851 \end{bmatrix} \begin{bmatrix} R_{2020} \\ G_{2020} \\ B_{2020} \end{bmatrix} \quad (21.2)$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.4123908 & 0.3575843 & 0.1804808 \\ 0.2126390 & 0.7151687 & 0.0721923 \\ 0.0193308 & 0.1191948 & 0.9505322 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix} \quad (21.3)$$

We can obtain the tristimulus values and hence the xy chromaticity coordinates of the RGB primaries with a combination of 1, 0, and 0 for the linear RGB values on the right-hand sides of Eqs. (21.2) and (21.3). For example, when



$(R_{709}, G_{709}, B_{709})$ is set to $(1, 0, 0)$, (X, Y, Z) is $(0.4123908, 0.2126390, 0.0193308)$, and then $(x = 0.640$ and $y = 0.330)$, as shown in TABLE 21.1. In this tutorial, seven digits past the decimal are used in the calculations because the sum of each row in Eqs. (21.2)–(21.5) becomes unity.

Once the 3×3 matrices for converting (R, G, B) to (X, Y, Z) are determined for different RGB chromaticities, we can convert the RGB values between the different sets of chromaticities through a 3×3 matrix. For example, Rec. 709 RGB values can be converted to Rec. 2020 RGB values through a 3×3 matrix of the multiplication of the inverse of the matrix in Eq. (21.2) and the matrix in Eq. (21.3) as follows:

$$\begin{bmatrix} R_{2020} \\ G_{2020} \\ B_{2020} \end{bmatrix} = \begin{bmatrix} 0.6274039 & 0.3292830 & 0.0433131 \\ 0.0690973 & 0.9195404 & 0.0113623 \\ 0.0163914 & 0.0880133 & 0.8955953 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix} \quad (21.4)$$

Likewise, the Rec. 2020 RGB values can be converted to Rec. 709 RGB values through a 3×3 matrix of the multiplication of the inverse of the 3×3 matrix in Eq. (21.3) and the 3×3 matrix in Eq. (21.2) or the inverse of the 3×3 matrix in Eq. (21.4) as follows:

$$\begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix} = \begin{bmatrix} 1.6604910 & -0.5876411 & -0.0728499 \\ -0.1245505 & 1.1328999 & -0.0083494 \\ -0.0181508 & -0.1005789 & 1.1187297 \end{bmatrix} \begin{bmatrix} R_{2020} \\ G_{2020} \\ B_{2020} \end{bmatrix} \quad (21.5)$$

Note that the matrix elements in Eq. (21.4) are within a range from 0 to 1, whereas those in Eq. (21.5) are out of this range. The Rec. 2020 RGB values are always within a smaller range compared to the Rec. 709 RGB values, whereas Rec. 709 RGB values become negative or higher than 1. This means that the Rec. 2020 RGB chromaticities lie outside the triangle defined by the Rec. 709 triangle. FIGURE 21.4 shows some examples. When $(R_{2020}, G_{2020}, B_{2020})$ is $(0.90, 0.05, 0.20)$, $(R_{709}, G_{709}, B_{709})$ gets a negative G_{709} value; $(0.81, -0.04, 0.10)$. We can easily find this also from a chromaticity diagram where the Rec. 2020 chromaticity coordinates lie outside the Rec. 709 RGB triangle. When $(R_{2020}, G_{2020}, B_{2020})$ is $(0.90, 0.20, 0.20)$, on the other hand, $(R_{709}, G_{709}, B_{709})$ becomes $(1.36, 0.11, 0.19)$. Although the chromaticity coordinates stay inside the Rec. 709 RGB triangle, it is out of the Rec. 709 *color gamut* because the lightness is too high. This example shows that the RGB triangle cannot be used to describe the color gamut, although it has been inappropriately called “color gamut” in the display industry for many years.

TABLE 21.1. xy chromaticity coordinates of the RGB primaries and white of Rec. 2020, Rec. 709, DCI-P3, and Adobe RGB.

Color	Rec. 2020	Rec. 709	DCI-P3	Adobe RGB
R	(0.708, 0.292)	(0.640, 0.330)	(0.680, 0.320)	(0.640, 0.330)
G	(0.170, 0.797)	(0.300, 0.600)	(0.265, 0.690)	(0.210, 0.710)
B	(0.131, 0.046)	(0.150, 0.060)	(0.150, 0.060)	(0.150, 0.060)
W	(0.3127, 0.3290)	(0.3127, 0.3290)	(0.3140, 0.3510)*	(0.3127, 0.3290)

* DCI-P3 RGB is sometimes also used with a D65 white point [21.30].

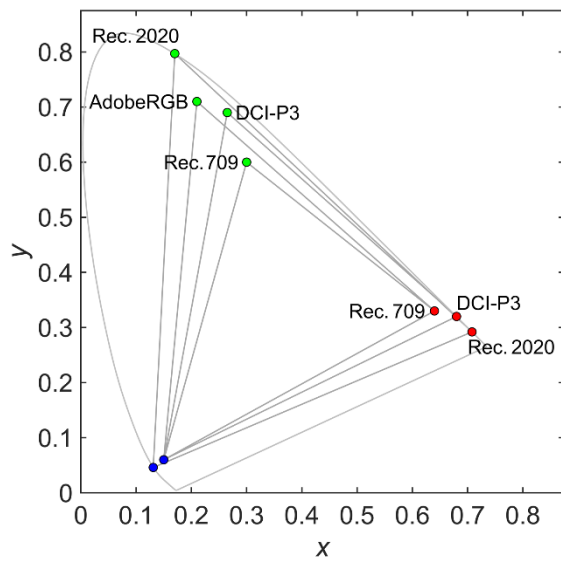


FIGURE 21.3. RGB triangles of Rec. 2020, Rec. 709, DCI-P3, and Adobe RGB in the xy chromaticity diagram.

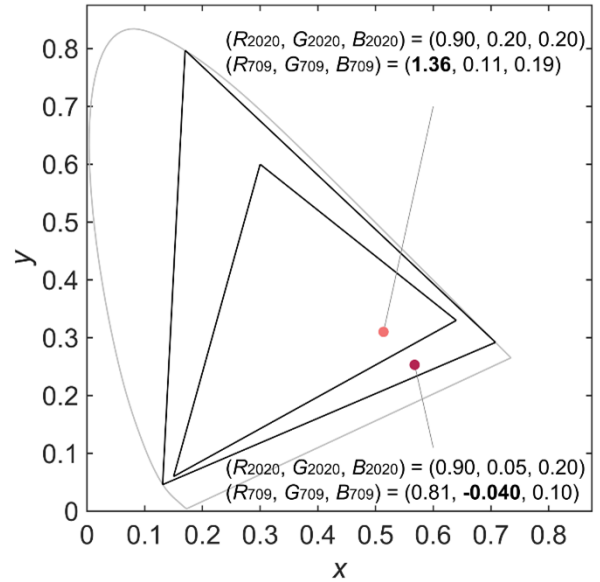


FIGURE 21.4. Rec. 2020 and Rec. 709 RGB triangles with two example colors out of the Rec. 709 color gamut.

21.3.2 Color Gamut is a Volume

To quantify the color gamut in a perceptually meaningful manner, a 3D perceptually uniform and homogeneous color space based on a color appearance model is required [21.31], [21.32]. The visualization, comparison, and analysis of display color gamut have a long history in the science of image reproduction and display metrology. According to the CIE nomenclature of color gamut [21.33], CIE 168:2005 [21.16], CIE 246:2021 [21.18], and IEC 62977-2-1[21.17], a color gamut is regarded as 3D in reproduction and media applications.

FIGURE 21.5 shows Pointer's colors [21.34] (representing the maximum gamut of real object colors) and the Rec. 709 and Rec. 2020 gamuts in the Yxy , $Yu'v'$, and CIELAB color spaces. The mean color difference data form ellipsoids of various sizes and orientations in the Yxy color space, which led to the creation of the CIELAB color space. This space is nominally perceptually uniform with spherical color difference solids assumed. In the Yxy and $Yu'v'$ color spaces, each gamut has a flat triangular base, *i.e.*, the RGB triangle formed by connecting the chromaticity coordinates of the RGB primaries) with three flat vertical walls that intersect at the roof, comprising three warped plates, thus creating an enclosed volume. The area of the RGB triangle base does not accurately represent the gamut volume in the Yxy and $Yu'v'$ color spaces because the solid is neither a triangular prism nor a triangular pyramid. The base RGB triangle begins to lack the blue corner at a low relative luminance. Therefore, the base RGB triangle area is proportional to the gamut volume in the Yxy and $Yu'v'$ color spaces only up to this low relative luminance. In addition, near-black colors sweep the xy and $u'v'$ planes, making the Pointer's gamut teardrop-shaped, whereas black converges to a point in the CIELAB color space.

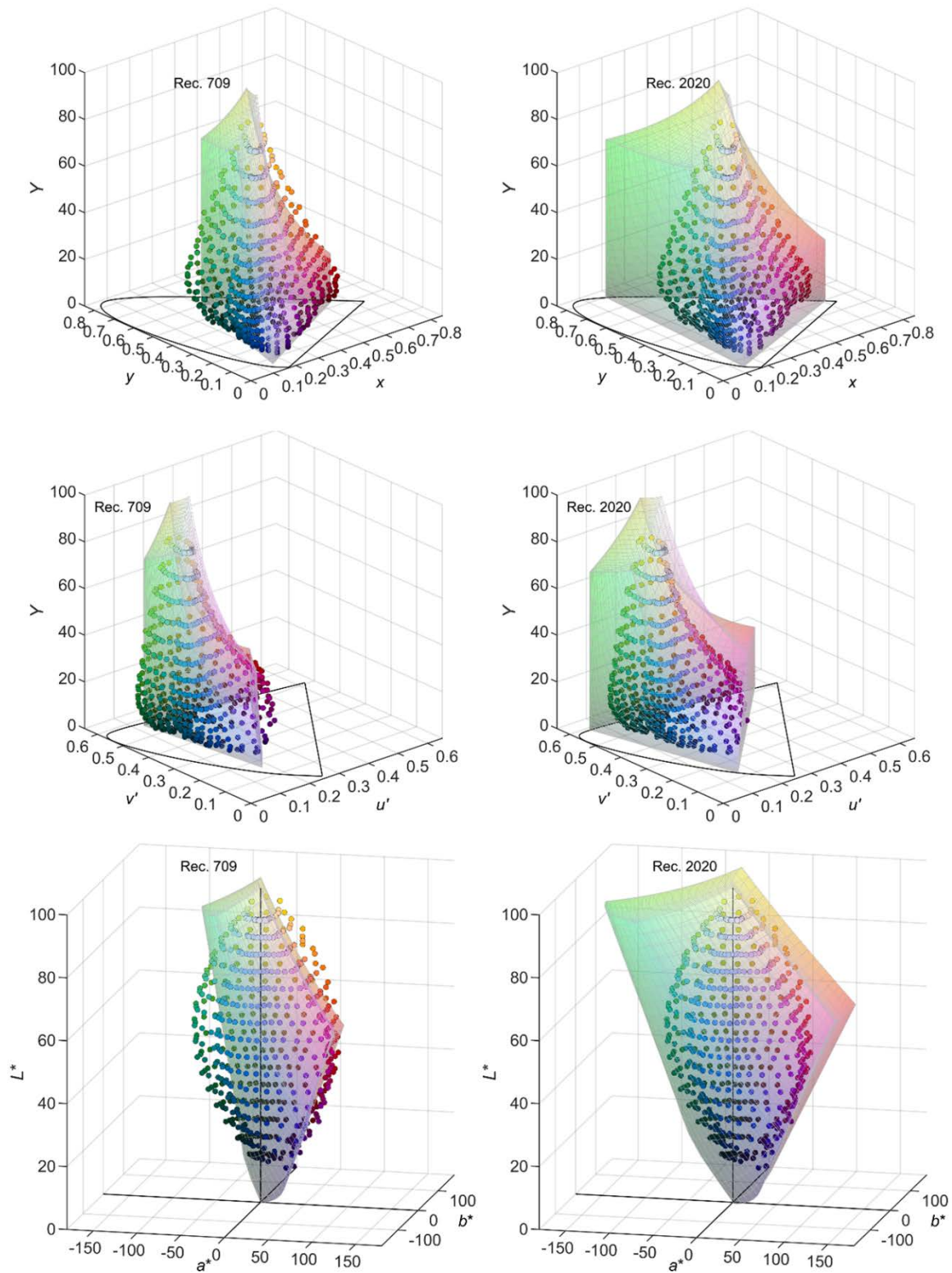


FIGURE 21.5. An example data set, Pointer colors, are shown here transformed to demonstrate the relative shapes under illuminant D65.



21.3.3 Color Gamut and Image Quality

The display color gamut indicates the range of reproducible colors. This concept is difficult to understand even for display engineers and color scientists, resulting in several misleading interpretations and exaggerations, one which usually relates image quality to the color gamut. It is generally accepted that a larger gamut volume suggests a better image quality, but the color gamut metric neither indicates the accuracy of the rendered colors, nor the number of discernible colors that can be displayed. The absolute location of the neutral axis of the gamut volume and overlap with the reference gamut are also important properties: Two gamut volumes may have the same size, but only one of them may cover all points of interest, while the other may not. Additionally, image quality also depends not only on metrological quantities such as color gamut, contrast ratio, and peak luminance, but also on host-side gamut- and tone-mapping algorithms, viewing conditions, image content, and subjective preferences. A display could also have geometrical distortion, blur, crosstalk, non-uniformity, and other spatio-temporal artifacts. Considering all this, it is therefore by far not sufficient to evaluate image quality solely by the color gamut.

21.3.4 Chromaticity Gamut Area

In many analyses, traditionally and even at present, the display color gamut is visualized and evaluated as a polygon (in most cases an RGB triangle) in the xy or $u'v'$ chromaticity diagram. However, there are several major problems with this approach, for example, the discrepancy between the areas in the xy and $u'v'$ chromaticity diagrams. Currently, many display engineers and researchers tend to use the $u'v'$ diagram for measuring and calculating the display “color gamut”, claiming a nominal perceptual uniformity [21.36]–[21.40]. However, this tendency is caused by the fact that the $u'v'$ area ratio to a reference color space, such as sRGB, is usually numerically larger than the xy area ratio [21.41], [21.42]. It should be noted that the chromaticity area cannot be referred to as a color gamut because it neglects the basic properties of color appearance as well as the important dimensions of lightness.

Although it is evident that the areal dimension in the xy chromaticity diagram is not meaningful in terms of “color gamut area” because the xy space is not perceptually uniform, xy chromaticity areas for additive RGB displays are highly correlated with the color gamut volumes calculated in any of the CIE color appearance spaces, including CIELAB, CIELUV, and CIECAM02 [21.41]. The result is counterintuitive for the CIELUV color space, because the $u'v'$ coordinates are precursors of the u^*v^* coordinates, as described in Appendix B1.2. In these color appearance spaces, chroma increases as lightness increases, which coincidentally enhances the suitability of the enlargement of the yellow and green regions of the xy diagram as a color gamut volume metric [21.43]. In fact, the CIELUV u^* and v^* scale linearly with L^* and a subtractive shift in chromaticity coordinates ($u' - u'_n, v' - v'_n$), where u'_n and v'_n are the chromaticity coordinates of reference white. Therefore, the xy area can be used as a proxy for 3D color gamut volume in additive RGB displays. By contrast, $u'v'$ chromaticity areas show no significant correlation with the 3D color gamut volumes in any color appearance spaces. FIGURE 21.6 shows Rec. 2020 RGB triangles delineated into CMY regions by the lines connecting the D65 white point and the RGB chromaticity points in the xy diagram. The $u'v'$ area overestimates the magenta region and underestimates the yellow region with respect to the gamut volume in those regions.

Note that the xy area as a proxy for color gamut volume is not applicable to multichromatic displays [21.1] because, unless the non-RGB optical color channel(s) is(are) completely turned off, it cannot be additive. Some researchers define the color gamut of a multichromatic display as the chromaticity area of a polygon connecting the vertices with the chromaticity coordinates of the optical color channels [21.44]. However, the chromaticity area only indicates the range of the reproducible chromaticities, without considering the corresponding luminance levels. Therefore, the polygon area cannot be used for estimating the color gamut volume. Also note that the xy area is invalid for comparing displays with different white points because chromatic adaptation is not considered. For consistent and meaningful color gamut comparisons, the metric needs a color space with a common chromatically adapted white point, which is not considered in legacy chromaticity gamut area metrics. A recent study reported high correlations of 0.98–0.99 between the xy chromaticity gamut area and color gamut volume for additive displays with a common white point corresponding to a correlated temperature of 6500 K and above [21.45].



21.3.5 Relative Gamut Metrics

Another consideration related to gamut metrics is the practice of using two different ratios: gamut size ratio, which compares relative sizes, versus the gamut coverage ratio, which is a measure of the intersection of a gamut with a reference (see Section 5.32.2). The term “Gamut” in this section and 21.4.1 may apply both to chromaticity area or color gamut volume. From FIGURE 21.4 it can be seen that Rec. 2020 is more capable of reproducing real object colors compared with the reference gamut Rec. 709. Among several candidates, the Rec. 2020 RGB primaries were more suitable for covering Pointer’s gamut [21.43]. Although Pointer’s gamut was intended to cover real-world reflective colors, there is imagery containing many colors that exceed Pointer’s gamut, for example computer graphics, animation, structural, or emissive colors in objects or phenomena such as butterfly wings, lighting, or fireworks. Gamut coverage is relative to a specific reference gamut, such as Rec. 709, DCI-P3, or Rec. 2020, or sRGB, and therefore can never be larger than 100%.¹

Even if a display has a large absolute gamut, the extent to which it covers the reference gamut is an important factor, colors rendered outside the reference gamut assumed by the input signal do not exist in the input signal and are thus “fabricated” by the display (gamut expansion). However, deliberate gamut expansion methods may be beneficial for displays under certain ambient conditions, provided that the expansion is properly adapted to the ambient. The gamut ratio measures the chromaticity area or color gamut volume of the display gamut relative to a reference gamut, and it can therefore be larger than 100%. For example, some manufacturers are touting “140% of Rec. 709”. However, even if a display has a (chromaticity) gamut area ratio above 100% of (for example) DCI-P3, its gamut area coverage or gamut volume intersection may actually be less than 100% of DCI-P3. The gamut coverage metric is more meaningful in terms of color reproduction accuracy than the gamut size ratio metric, provided that the colors inside the gamut are accurate

too. If color gamut volume or chromaticity gamut area of the reference gamut and display are expressed as G_{ref} and G_{disp} , respectively, the gamut coverage g_{cov} is expressed as

$$g_{\text{cov}} = \frac{G_{\text{disp} \cap \text{ref}}}{G_{\text{ref}}} \quad (21.6)$$

where $G_{\text{disp} \cap \text{ref}}$ is the gamut intersection volume or area. The absolute gamut size ratio g_{abs} is expressed as

$$g_{\text{abs}} = \frac{G_{\text{disp}}}{G_{\text{ref}}} \quad (21.7)$$

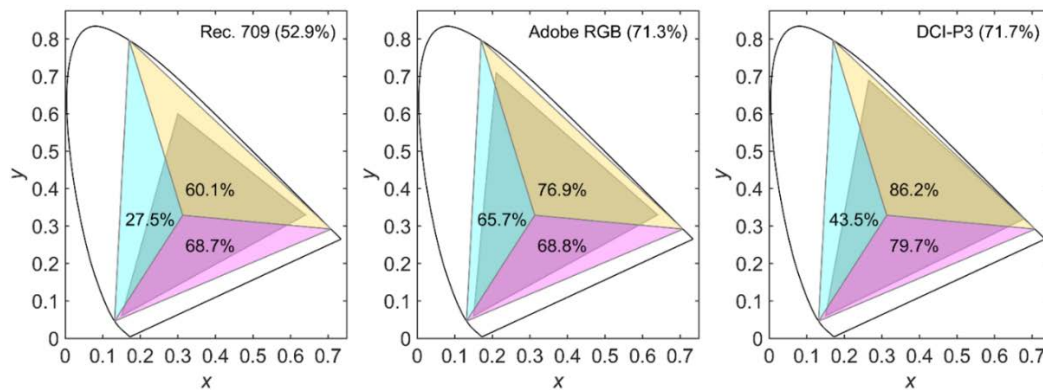


FIGURE 21.6. Chromaticity gamut area coverage ratios in Rec. 2020 CMY regions: Rec. 709 (left), Adobe RGB (center), and DCI-P3 (right).

¹ Note: The primary colorimetry of Rec.709 and sRGB are the same. However, there are differences in their gamut envelopes resulting from their unique tone response curves and the specified encoding methods. While very close to each other and often used interchangeably, they do have minor differences.



21.4. Gamut Shape

The display gamut shape (hull in the case of color gamut volume), rather than a single-valued gamut coverage ratio, is also important because it indicates where colors are or where they are not with respect to the reference color space, and also whether the display has hue mismatches with respect to a reference color space. Although the 3D plot of two gamuts can be translucent as shown in FIGURE 21.4, it is difficult to grasp the details when both gamuts are plotted as surfaces. Observing the 3D plot from different angles solves this problem but requires interactive 3D graphics. In this section, non-interactive 2D visualizations of display gamut shapes are therefore introduced.

21.4.1 CMY Chromaticity Gamut Area Coverage Ratios

The CMY chromaticity area coverage ratios are easy to compute and provide a practical approach to representing the color gamut volume coverage ratios in the CMY regions, provided that the display is additive (see Chapter 5.4 Color Signal White). The coverage ratios in the examples below are computed relative to the chromaticity areas of the Rec. 2020 CMY regions, delineated by straight lines connecting the chromaticity points of the Rec. 2020 W (which is D65) and RGB in the xy chromaticity diagram. If chromaticity gamut area of the display and the Rec. 2020 CMY regions are expressed as A_{disp} and $A_Q, Q: \{C, M, Y\}$, respectively, the calculated area coverage ratio of region Q , $A_{\text{cov},Q}$,

$$A_{\text{cov},Q} = \frac{A_{\text{disp} \cap Q}}{A_Q} \quad (21.8)$$

are proxies for the color gamut volume of the regions Q [21.46]. FIGURE 21.6 shows the Rec. 2020 chromaticity area coverage ratios and CMY area coverage ratios for the Rec. 709, Adobe RGB, and DCI-P3 reference color spaces. The Rec. 2020 ratios for Adobe RGB and DCI-P3 are both in the 71% range, whereas the cyan and yellow region coverage ratios of DCI-P3 have about 43% and 86% coverage, respectively. For Adobe RGB, on the other hand, the cyan and yellow coverage ratios are around 70%, thereby demonstrating a better balance of color gamut coverage with respect to hue. As mentioned in 21.3.4, this proxy metric using xy area is not applicable to multichromatic displays so for such displays we must take a volumetric approach and apply a 3D-to-2D visualization as explained in the next subsection.

21.4.2 Gamut Rings

Here, a 2D visualization of the display color gamut, named “gamut rings,” is introduced [21.1]. Gamut rings are composed of at least 10 rings concentric around the L^* axis of the CIELAB color space. The rings are plotted in a diagram with two axes of the root sum square of CIELAB a^* (a_{RSS}^*) and root sum square of CIELAB b^* (b_{RSS}^*) with the CIELAB hue angle retained. This diagram allows the area dimension to be used for volumetry. The rings are delineated with constant L^* loci. The area of each locus outward from the center numerically matches the volume of slices of the CIELAB gamut volume summed up from $L^* = 0$ to the L^* value of that locus. In the case of 10 rings, the area of the innermost locus (the first “ring” does not have any hole) numerically equals the volume of the CIELAB gamut envelope for $0 < L^* \leq 10$. The area of the next ring outward equals the volume for $10 < L^* \leq 20$, and so on. Ultimately, the last ring equals the volume for $90 < L^* \leq 100$. The outline area corresponds to the total color gamut volume. The width of the ring (distance between two loci of constant L^*) along any hue vector represents the steepness of the volume envelope along that hue vector in that L^* slice. By plotting the hue vectors of the reference color space in the gamut ring diagram, it is easy to identify the envelope of hue regions in which the gamut is different.

This section explains the principle of the gamut rings, whereas section 5.32 covers the implementation, including sample code. In CIELAB, L^* represents lightness and is normalized such that $L_{\text{max}}^* = 100$. To calculate the gamut rings, gamut boundary polygons in the $L^*a^*b^*$ color space are first obtained at lightness values L^* ranging from 0.5 to 99.5 in intervals of 1, thereby including 100 equidistant lightness values. The sum of the polygon areas multiplied with the L^* interval (=1) approximates the volume. FIGURE 21.7 shows a triangulated Rec. 2020 gamut surface (left) and 100 slices at $L^* = 0.5, 1.5, \dots, 99.5$, indicated by a 10-interval grayscale (right). The loci forming the display gamut boundaries are then transformed into gamut rings using the algorithm shown in FIGURE 21.8. First, the area of each constant- L^* locus



in a hue angle ranging from $h - 0.5^\circ$ to $h + 0.5^\circ$, $A(L^*, h)$, is obtained, where h ranges from 0° to 359° at intervals of 1° . The a^*b^* coordinates of the locus at hue angles of $h \pm 0.5^\circ$ are obtained by linear interpolation. The equivalent chroma value, $C^*(L^*, h)$, is obtained as

$$C^*(L^*, h) = \sqrt{\frac{360A(L^*, h)}{\pi}} \quad (21.9)$$

The root sum square (RSS) of the equivalent chroma values, at each hue angle in the lightness range from 0 to L^* , where L^* is an integer ranging from 1 to 100, $C_{\text{RSS}}^*(L^*, h)$, is then obtained as

$$C_{\text{RSS}}^*(L^*, h) = \sqrt{\sum_{k=1}^{L^*} C^*(k - 0.5, h)^2} \quad (21.10)$$

The $(a_{\text{RSS}}^*, b_{\text{RSS}}^*)_{L^*, h}$ coordinates of C_{RSS}^* at a hue angle h in the lightness range from 0 to L^* are defined as

$$(a_{\text{RSS}}^*, b_{\text{RSS}}^*)_{L^*, h} = (C_{\text{RSS}}^*(L^*, h) \cos h, C_{\text{RSS}}^*(L^*, h) \sin h) \quad (21.11)$$

FIGURE 21.9 shows the gamut rings of Rec. 2020 and Rec. 709 standards. The ring of highest lightness ($90 < L^* \leq 100$ slice) is very thin except at in the yellow hue direction; at the highest L^* the only significant contribution to the volume comes from yellow hues because only yellow remains chromatic when approaching white. FIGURE 21.10 shows the outer gamut rings of Rec. 2020 and Rec. 709 standards. The Rec. 2020 outer ring is divided into CMY regions, where the directions of the straight red, green, and blue spokes correspond to the CIELAB-metric hue angles of the full-on Rec. 2020. Note that these straight lines do not represent constant hue lines, which are not perfectly straight in CIELAB. The area ratios of the CMY regions of the Rec. 2020 gamut rings are closer to the CMY chromaticity area ratios in the xy diagram than that in the $u'v'$ diagram (see [21.46]). This supports the validity of the xy chromaticity gamut area metric as a proxy for color gamut volume. FIGURE 21.11 shows the Rec. 2020 gamut rings and their coverages with Rec. 709 [21.35].

For actual measurements of display color gamut volume, it is recommended to report the DUT's operating mode and the luminance (for direct-view displays) or luminous flux (for projectors) level for the white (255, 255, 255) patch with the gamut rings together. It is even better to report the tristimulus X and Z values, xy coordinates, and the CSW in addition to the Y value. The concept of gamut rings can be summarized as:

- Gamut rings are like cumulatively stacked annual growth rings. It is not a contour plot.
- Each ring represents the incremental volume within the corresponding L^* interval in which the hue angle is retained.
- The area dimension of the ring diagram can be used for the volumetry of the color gamut.
- The a_{RSS}^* and b_{RSS}^* axes represent the CIELAB green-red (a^*) and blue-yellow (b^*) hue directions, respectively.
- $C_{\text{RSS}}^*(h)$ is the cumulative RSS of C^* at a hue angle of h in the polar coordinates. a_{RSS}^* and b_{RSS}^* represent their Cartesian coordinates.

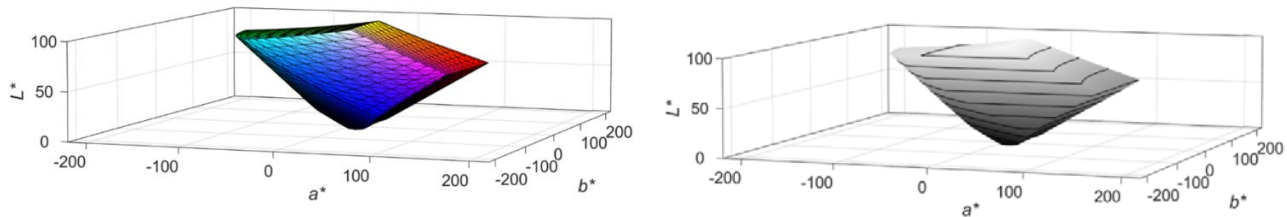


FIGURE 21.7. Triangulated Rec. 2020 gamut surface with 602 grid points (left) and 10 constant- L^* slices (right) in the D50 CIELAB color space.



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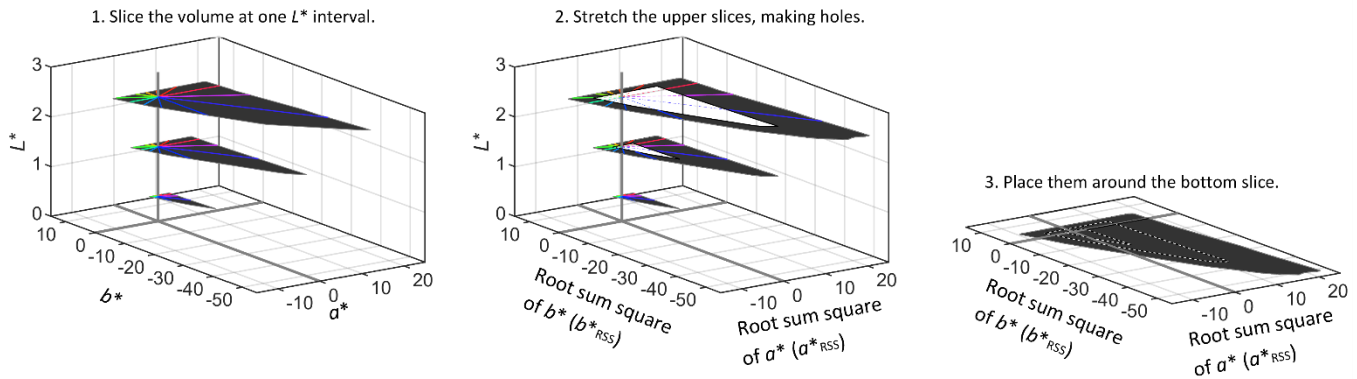


FIGURE 21.8. Schematic of gamut ring transform. Only the bottom three slices are illustrated as a simple example. This process will continue all the way to $L^* = 100$, with wider and wider rings.

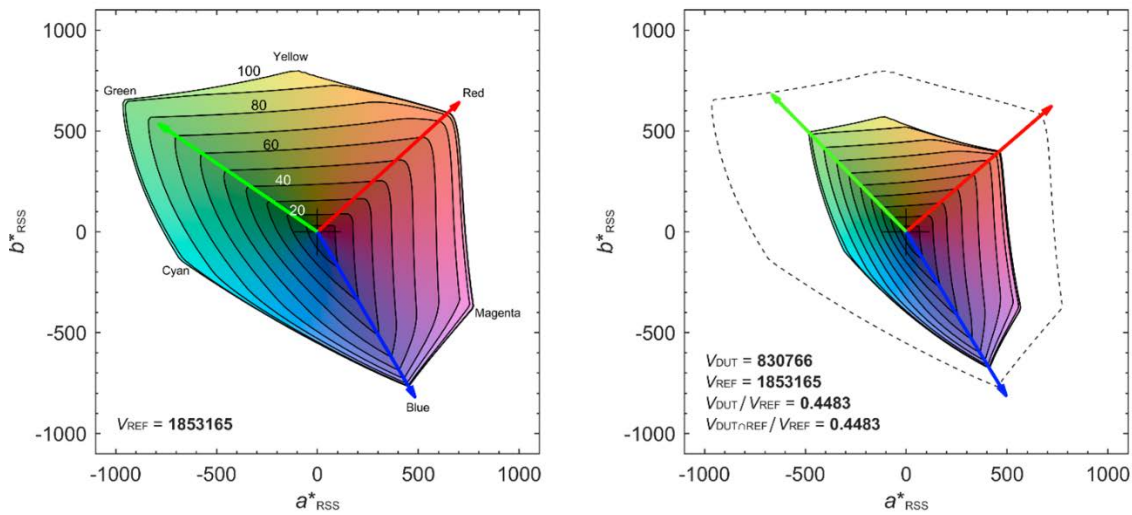


FIGURE 21.9. Rec. 2020 (left) and Rec. 709 (right) gamut rings. The dotted locus shows the outer Rec. 2020 gamut ring.

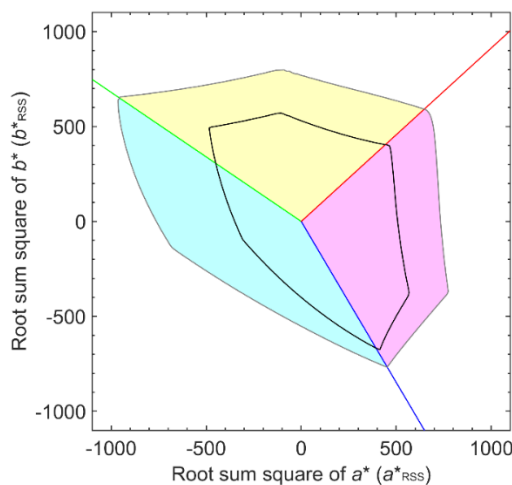


FIGURE 21.10. Outer gamut rings for Rec. 2020 and Rec. 709 standards with Rec. 2020 RGB hue angle spokes.

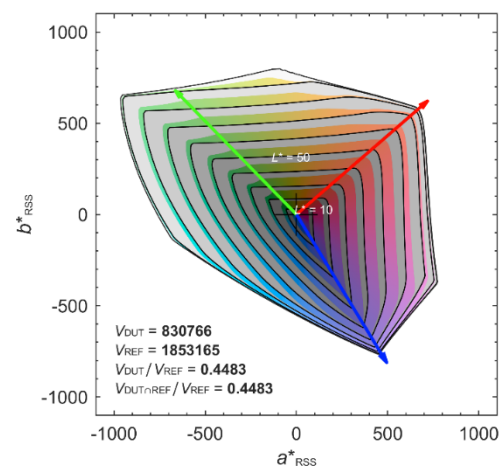


FIGURE 21.11. Gamut rings for Rec 2020 (grayscale) and coverages (colored) with Rec. 709 with Rec. 709 RGB hue angle spokes.



21.5. Light Measuring Device Considerations

Modern displays are making great strides in expanding their color gamut. Advances in light emitting diode (LED), quantum dot, and laser technologies have pushed the color capability of displays closer to the BT.2020 color space [21.24]. Although the narrower spectral bandwidth of LED and laser sources provide more saturated colors, the instrument used to measure those colors needs to be suitable for the task. Spectroradiometers are typically needed for lasers and narrow bandwidth LEDs since filter colorimeters are generally not accurate enough for these light sources [21.17]. However, the spectroradiometer must also have the necessary dynamic range and spectral bandwidth in order to sufficiently resolve the narrow spectral shapes often used in wide color gamut displays. The International Commission on Illumination (CIE) Technical Report CIE 233 provides an extensive description of important array spectroradiometer characteristics that can potentially impact the measurement of wide color gamut displays [Error! Reference source not found.]. A recent International

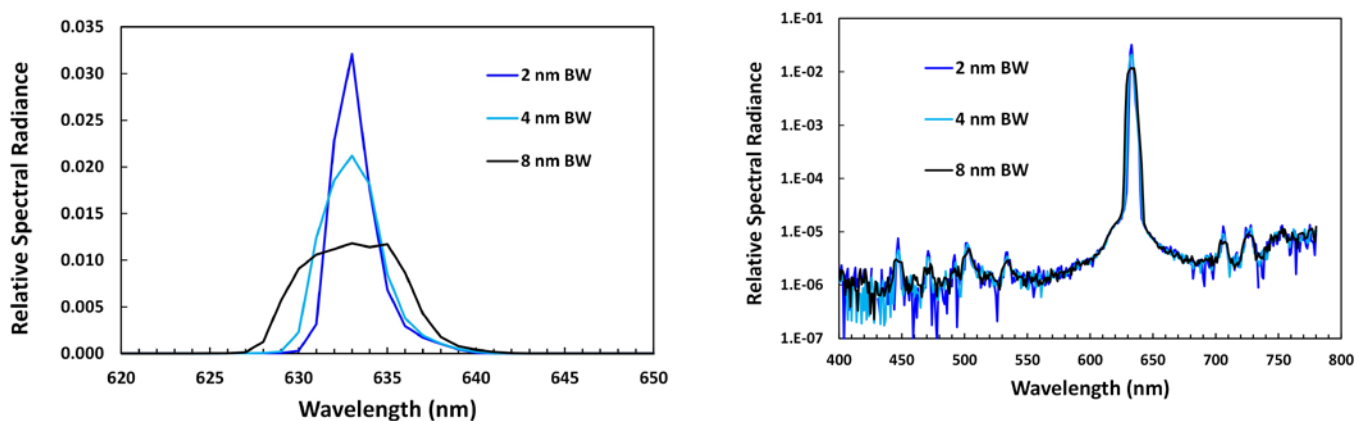


FIGURE 21.12. Relative spectral radiance of a Helium-neon red laser at 633 nm on a linear (left) and log (right) scale measured with an LMD using 2 nm, 4 nm, and an 8 nm spectral bandwidth.

Electrotechnical Commission (IEC) Technical Report IEC 62977-1-31 simulated how spectroradiometer characteristics like wavelength accuracy and spectral bandwidth affect chromaticity and chromaticity gamut area for displays with different color gamuts [21.48]. The following sections will further discuss the impact of spectroradiometer spectral bandwidth and signal-to-noise on the measured color and color gamut.

21.5.1 Chromaticity Dependence on LMD Spectral Bandwidth

It is generally known that as the spectral bandwidth of a light source increases, at very large bandwidths the broadband spectrum will appear as a certain white color temperature. This is graphically represented by the CIE 1931 and CIE 1976 chromaticity diagrams, where pure monochromatic colors define the spectrum locus of the chromaticity diagram, and broadband multi-wavelength sources lie in the middle. However, in practice, the ability of an LMD to accurately determine the chromaticity of a light source is strongly dependent on its spectral bandwidth. Traditionally the color accuracy of an LMD is specified relative to a broadband light source such as Illuminant A. Since most commercial spectroradiometers have spectral bandwidths smaller than 10 nm (full-width-at-half-maximum, FWHM), there is minimal influence of the spectral bandwidth on these broadband sources. But the LMD spectral bandwidth becomes more prominent when measuring the more saturated light sources in modern displays. The extreme case would be that of laser displays, where the primary colors are expected to lie on the spectrum locus. An example of the LMD spectral bandwidth dependence is illustrated in FIGURE 21.12.

A Helium-neon laser at 633 nm was used to illuminate an integrating sphere, and a variable spectral bandwidth LMD measured spectral radiance and chromaticity of the laser light at the sphere port. The Helium-neon laser spectra was measured with 2 nm, 4 nm, and 8 nm spectral bandwidths and is shown in FIGURE 21.12. The left figure



demonstrates the spectral broadening with larger LMD spectral bandwidth. For a constant total radiance (and luminance), the peak spectral radiance decreases as the spectral radiance is spread over a larger bandwidth. TABLE 21.2 shows how the measured CIE 1976 $u'v'$ chromaticity shifts from the ideal chromaticity of the monochromatic line source. The LMD chromaticity accuracy is specified as ± 0.0015 for Illuminant A by the manufacturer, but it is expected that the actual accuracy is significantly better in this case. The LMD chromaticity repeatability was found to be 0.0002. The table shows a $\Delta u'v'$ chromaticity shift of 0.0032 even for the relatively small 2 nm spectral bandwidth. Further increases in spectral bandwidth had a more modest effect for this wavelength. The chromaticity coordinates for the Helium-neon spectra measured at the three spectral bandwidths are shown in the CIE 1931 chromaticity diagram in FIGURE 21.13. The impact of the spectral background will be discussed in the next section.

TABLE 21.2. CIE 1976 chromaticity shift ($\Delta u'v'$) with increasing LMD spectral bandwidth of a Helium-neon source relative to the ideal monochromatic chromaticity at 633 nm. The data shows the chromaticity shift as measured compared to when the background level is subtracted.

LMD Spectral Bandwidth	CIE 1976 Chromaticity Shift ($\Delta u'v'$)	
	Measured spectra	Background subtracted
2 nm	0.0032	0.0001
4 nm	0.0037	0.0007
8 nm	0.0045	0.0014

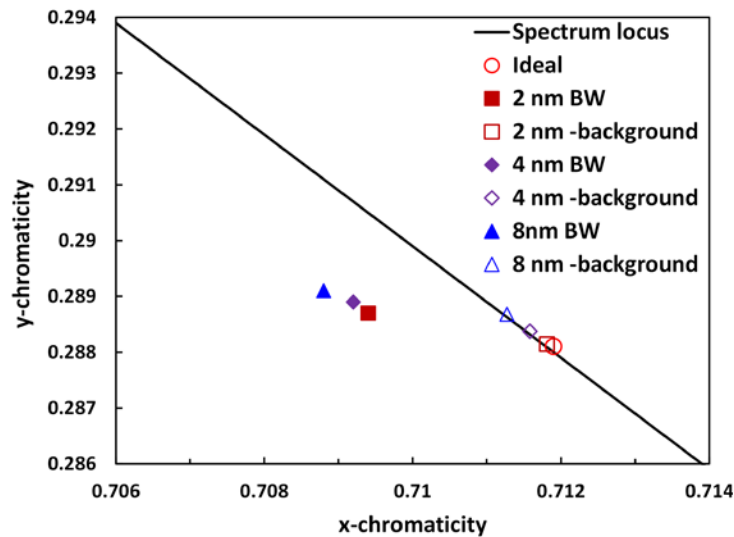


FIGURE 21.13. CIE 1931 chromaticity diagram of Helium-Neon laser spectra measured by an LMD with 2 nm, 4 nm, and 8 nm spectral bandwidth (BW). Solid marks indicate as-measured data, while unfilled marks show same data with background-subtraction applied.

However, the influence of LMD (and light source) spectral bandwidth on chromaticity also depends significantly on the wavelength of the light. This is illustrated by the simulation shown in FIGURE 21.14. In this simulation, the spectra at each center wavelength are assumed to have a Gaussian line shape. The figure shows how the chromaticity at each center wavelength, represented by the wavelengths on the spectrum locus, shifts toward white as the FWHM bandwidth of the spectra increases. It is informative to recognize that the strongest spectral bandwidth dependence is for green colors, especially near 520 nm where the spectrum locus has the largest curvature. The behavior of the saturated red colors also agrees with the data that was observed in FIGURE 21.13. These results suggest that the spectral bandwidth of the LMD needs to be less than 5 nm for most saturated colors, and especially for saturated green colors. The influence of the LMD spectral background on chromaticity is discussed in the next section.

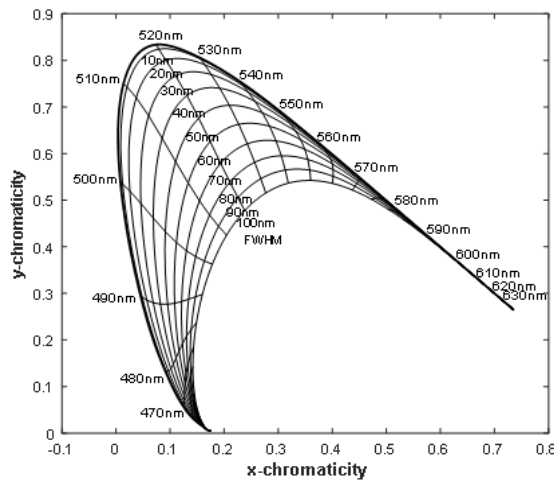


FIGURE 21.14. CIE 1931 chromaticity diagram where contour lines illustrate the chromaticity shift of a given central wavelength with increasing spectral bandwidth (FWHM).

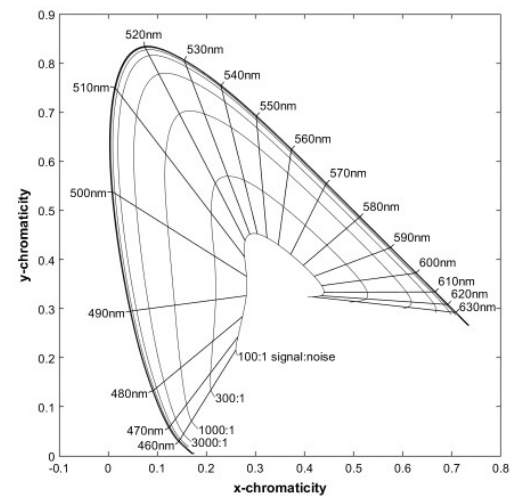


FIGURE 21.15. CIE 1931 chromaticity diagram where contour lines illustrate the chromaticity shift of a given wavelength with increasing background level (signal-to-noise ratio).

21.5.2 Chromaticity Dependence on LMD Dynamic Range

Every LMD has a background signal level that defines its dynamic range for a given measurement condition. This dynamic range is illustrated in the log plot of the Helium-neon laser spectral radiance data shown in FIGURE 21.12 (right). It indicates that the background level was about 4 decades below the peak spectral radiance. Techniques such as spectral stray light correction (to be discussed later) and averaging multiple measurements can help reduce the background, but a background level will eventually limit the LMD performance. An indication of how much the background level contributes to the chromaticity value can be determined by setting the spectral radiance at wavelengths below 600 nm and above 700 nm to zero. TABLE 21.2 shows that the background-subtracted spectra had a significantly reduced chromaticity shift and demonstrates the need for LMDs with high dynamic range in order to accurately measure highly saturated light sources like lasers. It is also informative to compare the measured and background subtracted chromaticity data as plotted in the CIE 1931 chromaticity diagram (see FIGURE 21.13). It shows that the background signal pushed the chromaticity values toward white. But the background-subtracted data for this saturated red color shows that increases in spectral bandwidth principally move the chromaticity up the spectrum locus line.

However, the influence of the LMD dynamic range on the measured chromaticity can vary depending on the color to be measured. The dependence of the LMD background level on chromaticity can be evaluated by generating synthetic spectra created at 1 nm increments, with a single normalized peak (Dirac delta) at a desired wavelength. All other wavelengths in each spectrum are scaled to a defined background level to achieve a certain signal-to-noise relative to the peak. FIGURE 21.15 shows how the chromaticity of a given wavelength changes as the signal-to-noise level increases. It highlights the fact that the spectroradiometer must have a large dynamic range (~4 decades) in order to measure chromaticities approaching the spectrum locus. Again, the green chromaticities are the most sensitive to the background level (signal-to-noise). Therefore, improvements in reducing the background level can improve the chromaticity accuracy of saturated colors.

The combined effect of LMD spectral bandwidth and dynamic range on the chromaticity gamut area can be illustrated for the demanding case of an ideal BT.2020 display. The simulated methods used to create FIGURE 21.14 and FIGURE 21.15 were applied to the BT.2020 primaries having peak wavelengths at 630 nm, 532 nm, and 467 nm. By varying the FWHM of the primary spectral, and incrementing the background level of each spectrum, the simulation can calculate the CIE 1931 chromaticity gamut area for a given combination of spectral bandwidth and background



level. FIGURE 21.16 shows the results of this analysis where the dependence of the LMD spectral bandwidth and background level are represented by contour lines indicating the fractional CIE 1931 chromaticity gamut area relative to an ideal BT.2020 area. The figure highlights the need for lower LMD spectral bandwidth and higher dynamic range in order to measure wide color gamut displays more accurately.

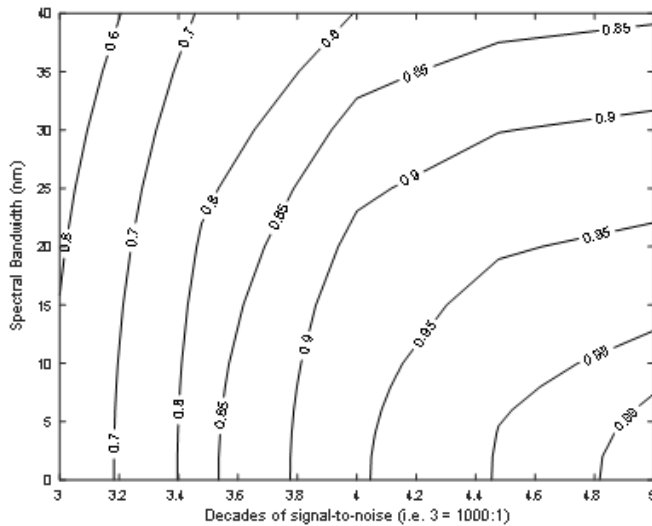


FIGURE 21.16. CIE 1931 chromaticity diagram where contour lines illustrate the chromaticity shift of a given wavelength with increasing background level (signal-to-noise ratio).

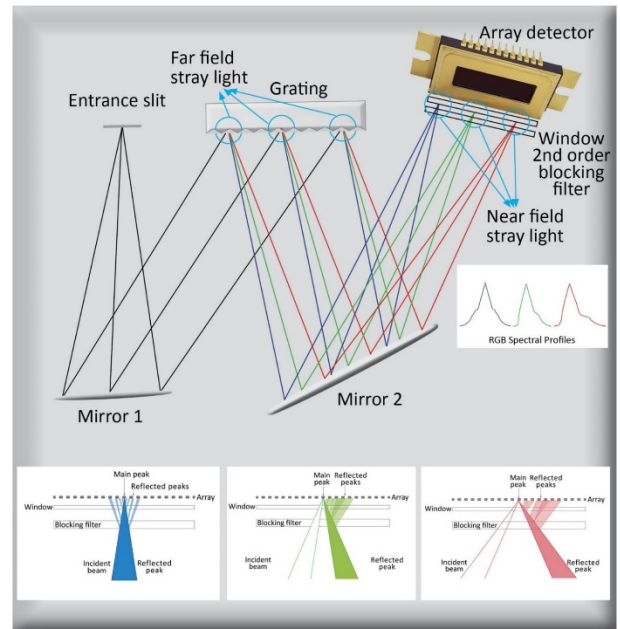


FIGURE 21.17. Schematic example of far field and near field spectral stray light created within a typical spectrometer. The bottom figures illustrate the near field spectral stray light created by multiple reflections near the detector and its dependence on the incident angle.

21.5.3 Spectral Stray Light Correction

Spectroradiometer manufacturers have made great strides in improving the performance of these LMDs. LMDs with spectral bandwidths of less than 5 nm are now readily available. However, the smaller bandwidths means that less light is incident on the detector array elements. This tends to negatively impact the dynamic range of the LMD. In applications like near-eye displays, the diameter of the LMD entrance pupil will typically need to be less than 5 mm, which further reduces the light on the detector. Manufacturers have tried to address the low light levels on the detector by using more sensitive sensors and cooling the sensor. However, these improvements can ultimately be overwhelmed by stray light contamination in the LMD. The influence of stray light on array spectroradiometer characteristics is discussed extensively in CIE 233 [21.47]. Spectral stray light within the LMD is of particular concern for color measurements. As the spectral bandwidth of the display primaries get narrower, the influence of spectral stray light within the spectroradiometer becomes increasingly important in measuring chromaticity and color capability. Light scattering within the optics and dispersive elements of the spectroradiometer broaden the true spectra and increase the background noise. FIGURE 21.17 shows a typical spectrometer configuration and highlights some of the origins of spectral stray light. Far field stray light can come from light scattering from gratings, walls, and optical surfaces [21.47]. It often produces a broad spectral background that can limit the dynamic range of the LMD. The near field stray light is often produced by multiple reflections that occur from optical surfaces near the detector array. These reflections can cause spectral features (shoulder) adjacent to the true spectral peak and broaden the spectrum asymmetrically depending on the incident angle (see bottom of FIGURE 21.17 and RGB spectral profile inset in middle right). However,



spectral stray light correction (SSLC) can be applied during the spectroradiometer calibration to limit the impact of this scattering on color measurements [21.49].

It is informative to illustrate the impact of SSLC on the color measurement. FIGURE 21.18 and FIGURE 21.19 show the relative spectral radiance (log scale) of white and the primary colors of an RGB laser display measured by the same LMD with and without SSLC applied. The log plots of the primary spectra indicate that there is light leakage in the display from the adjacent primaries that can potentially desaturate the primary color. The plots also highlight the benefit of SSLC in lowering the wings of the primary peak, as well as the background, by half to one decade in this case. This spectral stray light is also significant when multiple primaries are activated. As shown by the example of the white spectra, the spectral stray light from adjacent primaries overlap to further raise the background level. The practical impact of the SSLC on the white and primary chromaticity is summarized in TABLE 21.3. The chromaticity shifts (expressed in terms of the CIE 1976 chromaticity difference $\Delta u'v'$) illustrate the significant improvement in the chromaticity measurement that can be achieved with SSLC.

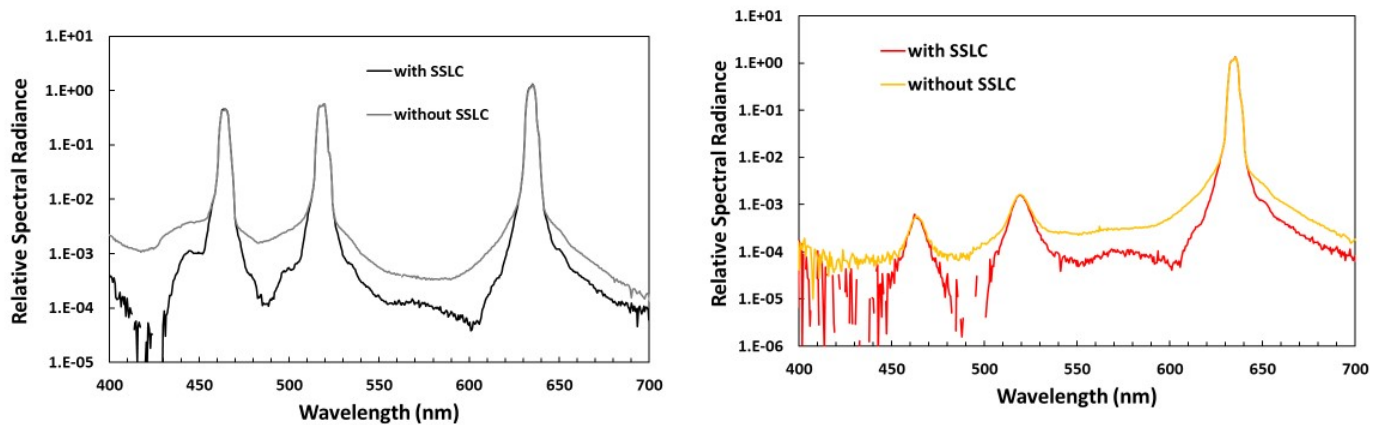


FIGURE 21.18. Log plots of white and primary spectra of a laser display measured with and without SSLC.

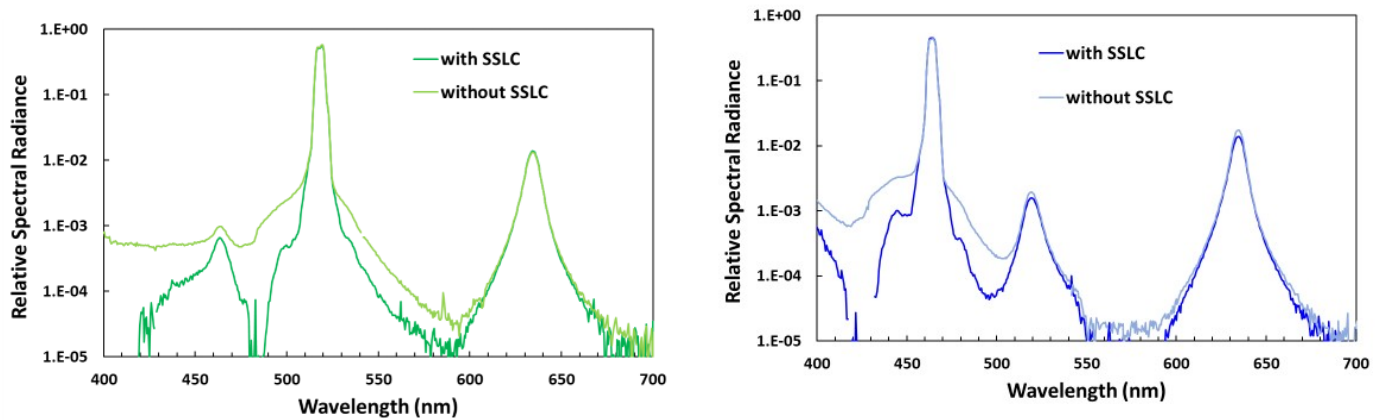


FIGURE 21.19. Log plots of white and primary spectra of a laser display measured with and without SSLC.

TABLE 21.3. Shift in chromaticity due to spectral stray light.

Color	White	Red	Green	Blue
$\Delta u'v' + 0.0004$	0.0054	0.0045	0.0027	0.0040



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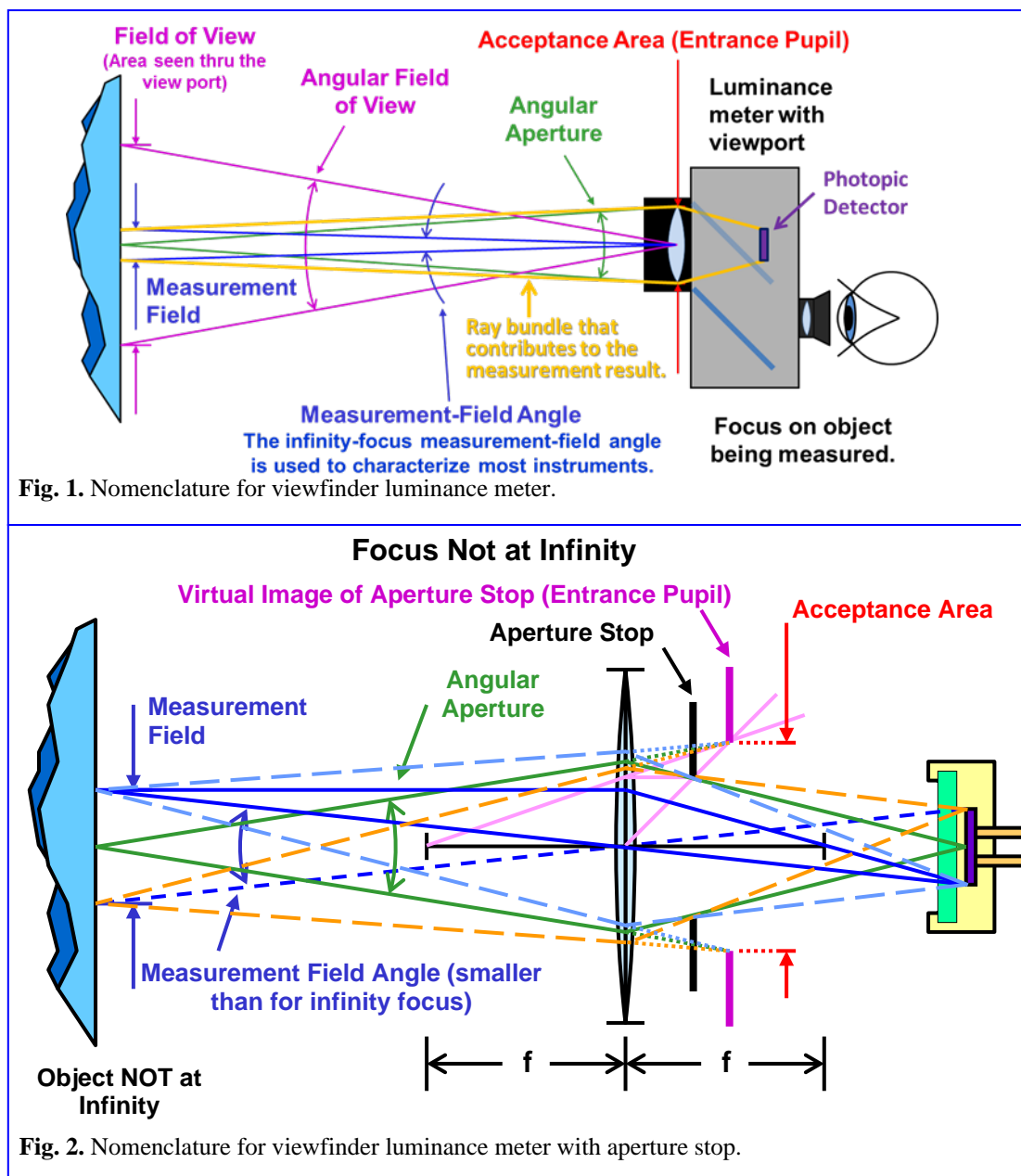
A. METROLOGY CONSIDERATIONS

Here we detail the general requirements for light measurements and the methods involved in properly using light-measurement devices (LMDs) or detectors. Most expect too much from their equipment, often thinking the measurement equipment performs perfectly under any different condition. The biggest problem is not realizing the sometimes-serious effects that scattered light within the detector can have on the measurement result. Please pay careful attention to § A2 Stray Light Management and Veiling Glare.



A1 LIGHT-MEASUREMENT DEVICES (LMDs) — DETECTORS

We first discuss the uncertainty requirements because that is usually what is of greatest interest to the experienced. We then describe a number of light-measurement devices (LMDs) or detectors that are used to measure the characteristics of displays. The next main section (§ A2 Stray-Light Management & Veiling Glare) discusses the very serious problems associated with stray light. To remind you of the terminology for photometers, we repeat here the diagrams from § 3.7:





A1.1 GENERAL UNCERTAINTY REQUIREMENTS OF THE LMD

There are many factors that contribute to the confidence that the measurements we make actually reflect the value of the measurand. A complete description of all the factors that can affect measurement uncertainties is found in CIE Publication No. 69, *Methods of Characterizing Illuminance Meters and Luminance Meters*. For a discussion of the propagation of errors and uncertainty estimations see § A10 Uncertainty Evaluations in this Metrology Appendix, and for the correct terminology see B21 Statements of Uncertainty in the Tutorial Appendix. Any uncertainty values are expressed using an expanded uncertainty with a coverage factor of $k = 2$ (in older terminology, a “two-standard-deviation” or “two-sigma” estimate)—see B21 for more details.

We invoke the CIE criterion of specifying the relative spectral responsivity from the human photopic response curve $V(\lambda)$ for both luminance and illuminance measurements. (See CIE Publication No. 69, *Methods of Characterizing Illuminance Meters and Luminance Meters*, p. 9, 1987.) Let $s(\lambda)$ be the response of the photopic detector to the spectrum $S(\lambda)$ (such as Illuminant A, a tungsten-halogen lamp at 2856 K), the error f_1' is defined as

$$f_1' = 100 \% \cdot \frac{\int_0^\infty |s^*(\lambda)_{\text{rel}} - V(\lambda)| d\lambda}{\int_0^\infty V(\lambda) d\lambda}, \text{ where } s^*(\lambda)_{\text{rel}} = s(\lambda) \frac{\int_0^\infty S(\lambda) V(\lambda) d\lambda}{\int_0^\infty S(\lambda) s(\lambda) d\lambda}. \quad (1)$$

The factor f_1' is representative of the deviation of the relative spectral responsivity from the $V(\lambda)$ curve.

For illuminance measurements, we invoke another CIE criterion that specifies the directional response of the illuminance meter, f_2 , defined as follows: A small light source is moved about in front of the illuminance meter held at a constant radius. The source is placed at least 20 times the largest of either the source diameter or diameter of the acceptance area of the illuminance meter. The directional response is

$$f_2(\theta, \phi) = \left(\frac{E(\theta, \phi)}{E(0, \phi) \cos \theta} - 1 \right) \cdot 100 \% , \quad (2)$$

where $E(0, \phi) = E(\theta = 0)$ is the illuminance measured with a source at the normal position (independent of ϕ at normal), θ is the inclination angle from the normal, and ϕ is the axial angle from the x -axis. For axial symmetry (or assumed axial symmetry) we have

$$f_2(\theta) = f_2(\theta, \phi), \quad \text{for axial symmetry.} \quad (3)$$

For a single number for the directional response, the CIE defines

$$f_2 = \int_0^{85^\circ} |f_2(\theta)| \sin 2\theta d\theta, \quad (4)$$

where the integration is not taken to the full 90° to avoid infinities from the cosine ($85^\circ = 1.48353 \dots \text{rad}$).

Luminance Meters: For CIE Illuminant A: The luminance relative expanded uncertainty of measurement with coverage factor of two must be $u_{\text{LMD}} \leq 4 \%$ of the luminance, and the luminance measurement repeatability must be less than either a maximum of $\sigma_{\text{LMD}} = 0.4 \%$ of the luminance or the uncertainty introduced by any digitization (whichever is larger) over a 5 min interval. The deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f_1' \leq 8 \%$.

Illuminance Meters: For CIE Illuminant A: The illuminance relative expanded uncertainty of measurement with coverage factor of two must be $u_{\text{LMD}} = 4 \%$ of the illuminance or less, and the illuminance measurement repeatability must be less than either a maximum of $\sigma_{\text{LMD}} = 0.4 \%$ of the illuminance or the uncertainty introduced by any digitization (whichever is larger) over a 5 min interval. The deviation of the relative spectral responsivity from the $V(\lambda)$ curve must be $f_1' \leq 8 \%$. The directional response error must be $f_2 \leq 2 \%$.

Color Measurements: For CIE Illuminant A: For all instruments measuring color, the expanded uncertainty U_{col} with a coverage factor of two in measurement of (x, y) chromaticity coordinates must be $U_{\text{col}} \leq 0.005$ with repeatability $\sigma_{\text{col}} \leq 0.002$.

Radiance Measurements: Spectroradiometers that are most often used for display measurements utilize a ruled or holographic diffraction grating. These gratings are most sensitive at or near the blaze wavelength of the diffraction element (ruled or holographic grating). The blaze wavelength is that wavelength at which the grating is most efficient. Therefore, uncertainty for these devices depends upon wavelength. For the purposes of luminance, illuminance, and color measurements, a spectroradiometer with a wavelength range of 380 nm to 780 nm measuring a spectrally calibrated CIE Illuminant A



radiance or irradiance standard, the expanded uncertainty U_{LMD} with a coverage factor of two shall be $\leq 2\%$ for the 400 nm to 700 nm range and $\leq 5\%$ for the 380 nm to 400 nm range and the 700 nm to 780 nm range.

Array Detectors: However, the array detector is used; the above measurement requirements must be met. In addition, there are uniformity requirements that must be met. In a luminance measurement of a CIE Illuminant A uniform source in an appropriate configuration (usually specified by the manufacturer), we set the exposure to give $50\% \pm 10\%$ of the saturation level of the array (8-bit array saturates at 256, 16-bit array saturates at 65 536), then we obtain the average level of the entire array, S_{ave} ; the uniformity requirement is that the average over any 10×10 -detector-pixel measurement region S_{10} must be within 2% of the entire array average S_{ave} ; that is, $|S_{10} - S_{ave}|/S_{ave} \leq 0.02$. Hopefully, you will get an array detector that has an average nonuniformity better than this. If such LMDs are used to resolve fine detail at the pixel level of the display, then the smallest feature of interest should be rendered by at least ten detector pixels in the horizontal or vertical direction—if at all possible. See § A9 Array-Detector Measurements for a discussion of the complications that can arise when array detectors are used.

A1.2 MEASUREMENT-FIELD ANGLE & ANGULAR APERTURE OF LMD

For imaging LMDs the measurement field angle (MFA) must be 2° or less for infinity focus. Further, the angle subtended by the lens of the LMD from the center of the screen—the angular aperture—must also be 2° or less. There may be optical configurations that do not produce images on the photodetector of the LMD. This criterion is then equivalent to stating that all the rays coming from any pixel which contributes to the measurement made by the LMD must fall within a cone with apex angle of 2° or less. Further, all the rays coming from the centers of the measured pixels must be within 2° of the viewing direction. If the LMD used has a measurement field angle or angular aperture larger than 2° then its suitability must be tested with the type of DUT being measured as indicated below.

A1.2.1 DIAGNOSTIC: ANGULAR-APERTURE SUITABILITY OF LMD

The angular aperture or angle subtended by the LMD acceptance area (e.g., lens) may be important to good measurements. If the display exhibits a viewing-angle dependence, then the finite solid angle subtended by the LMD can have an effect on the measurement. The LMD should be placed a sufficient distance from the display or the LMD must be designed so that the change in luminance or color over the surface of the lens (or aperture) of the LMD for any displayed level from white to black or any color is essentially within the reproducibility of the LMD. Note: some configurations are collimated and can have a wide lens yet only use a small angular cone of light from each pixel (see B19 Collimated Optics). Also, some systems use a lens near the screen together light from most of the hemisphere in front of the pixels that are suitable for use with this document (see B24 Conoscopic LMDs).

A1.2.2 DIAGNOSTIC: QUALIFYING ANGULAR-APERTURES GREATER THAN 2°

This document suggests that the angular aperture or angle subtended by the lens (or entrance pupil) of the LMD (or each of its elements if it is an array detector) should be no greater than 2° . Suppose you want to use a LMD having a lens (or other means of gathering light) that has a subtense angle of greater than 2° as measured from the center of the screen, and you want to see if it is suitable for making measurements of a display. Let the subtense angle of the lens be θ_L . Take ten measurements at the normal position ($\theta = 0$) and calculate the mean μ and standard deviation σ . Move to $\theta = +\theta_L/2$ and take ten measurements calculating a new mean μ' and standard deviation σ' . Then move to $\theta = -\theta_L/2$ and take ten measurements calculating a new mean μ'' and standard deviation σ'' . If the means μ' and μ'' are within σ of μ , then it should be safe to use the LMD with a larger subtense for that display. If the standard deviations are not all about the same (σ , σ' , and σ'' should all be about the same, certainly within a factor of two) your display or LMD may be drifting (or whatever), and you cannot trust your measurements until you figure out what is going on. The value for σ should be approximately the repeatability of the LMD. Why ten measurements? With ten measurements you can be almost 99% sure that the mean you measure is within a standard deviation of the “true” mean of the parent distribution—provided nothing is wrong, no drift in the DUT or LMD, no temporal aliasing, etc.

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>



A1.3 TYPE OF LMDs

In this document we primarily talk about luminance meters, which have a viewing port, and illuminance meters. There are some measurement apparatuses that are designed to be positioned close to the screen or even directly in contact with the screen. We want to include as many measurement options as possible.

A1.3.1 VIEWPORT LMDs

LMDs with viewports show the area being measured on the object by creating an image of the object using a lens and then sampling part of that image to produce the measurement. Many of these LMDs have a viewport or viewfinder (either optical or video) so the lens focuses the image of the object to be measured onto the detection aperture. It is always important to properly focus the device so that the image lies essentially in the plane of the measurement aperture. When using the eye to focus the instrument, it is easy to be fooled into thinking that it is properly focused when it is not. Here is a procedure to assure proper focus:

Parallax Method for Viewfinder Focus: First the viewfinder eyepiece is focused so that the target denoting the measurement field is sharply in focus and comfortable to view (many use an infinity focus, some use a focus that is at a reading distance). As you look at the object to be measured, if its image in the viewfinder moves relative to the measurement field (the dark spot in the illustration in Fig. 3) as you make small transverse movements with your eye, then the LMD is not properly focused. When we say small transverse motions of the eye, what you do is move your head back and forth (left and right or up and down) just a few millimeters while looking through the eyepiece having the image and measurement field spot in view. Focus the main lens of the LMD until small transverse movements of the eye do not show any relative motion or parallax of the image with the measurement field spot or aperture. This has been called the parallax method of focusing a device.

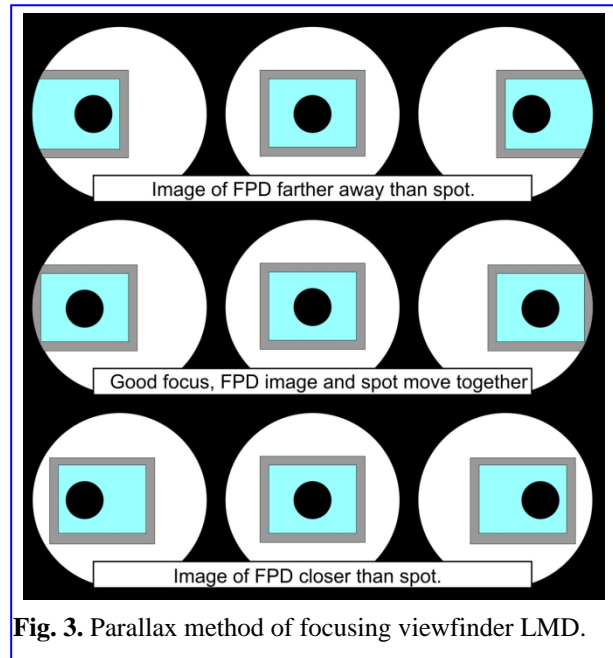


Fig. 3. Parallax method of focusing viewfinder LMD.

A1.3.2 CONOSCOPIC LMDs

Conoscopic LMDs use a lens that is in close proximity to the display and are able to capture much of the display characteristics over almost the entire hemisphere in front of the display. Care must be exercised to avoid touching any delicate display surfaces in using these devices. Since they employ array photodetectors, the requirements are presented above (Array Photodetectors), and further discussion of array-detector complications can be found in A9 Array-Detector Measurements. More information about conoscopic devices, how they work and how to perform diagnostics, can be found in § B24 Conoscopic LMDs.

A1.3.3 LARGE-MEASUREMENT-FIELD-ANGLE DETECTORS

If a display technology exhibits viewing angle characteristics (other than nearly Lambertian behavior) unacceptable errors can be introduced by a detector with a large measurement-field angle much greater than 2° . If the FPD technology for the DUT has no viewing angle dependence, then these types of detectors may sometimes be used. The use of such detectors must be verified that the results obtained are equivalent to LMDs meeting the above specifications (A1.1). Some of these devices are held against the DUT by a suction cup and will affect the display performance because of mechanical stresses. Before any such device is used, it should be tested for use with the DUT to assure its adequacy.

A1.3.4 DETECTORS WITH COLLIMATED OPTICS

Detectors with collimated optics are explained in B19 Collimated Optics. The lens for such detectors can be rather close to the display surface and give the appearance of subtending too large an angle. However, if properly designed, these detectors meet the above $\leq 2^\circ$ requirement both for measurement-field angle and angular aperture.

A1.3.5 MICROSCOPES & PROXIMITY DETECTORS CLOSE TO DISPLAY SURFACE

Other lens configurations exhibit similar problems of having a large solid angle for gathering light. If a microscope or a close-up lens is used with a camera (array detector), then the apex angle of the cone defined by the light-gathering lens from the viewpoint of the display surface may exceed the 2° angular-aperture requirement for the LMD lens that this document



specifies. Their adequacy would therefore have to be tested. For such instruments in close proximity to the screen, there is an additional source of contamination, reflections off the instrumentation back onto the screen thereby affecting the measurement results. If a camera is used where high magnification is required, it is best to use long-focal-length macro lenses and/or extension tubes with a long-focal-length lens (100 mm focal length and longer).

Glare in the lens system, if employed, should always be anticipated. Some detectors touch the screen with a suction cup, soft fabric, or a spider-type holder. Their suitability must be tested and proven for the type of display being used. Some screens are sensitive to mechanical stresses and devices that touch the screen too hard may prove to be completely unacceptable because of the mechanical perturbations. Some proximity devices also have an angular aperture angles and/or measurement field angles that are too large and provide a different result than would be obtained with a 2° instrument. Such instruments need to be tested for their adequacy by comparison with an instrument that meets the $\leq 2^\circ$ angular-aperture (lens subtense) and $\leq 2^\circ$ measurement-field requirements.

A1.3.6 LONG-DISTANCE MICROSCOPES

Long-distance microscopes generally avoid producing significant reflections of light back onto the screen that would corrupt a measurement. However, they often have lenses with large diameters in order to provide good resolution and gather more light, and they can exceed the $\leq 2^\circ$ angular aperture (lens subtense) of the LMD lens that this document specifies. Their adequacy would therefore have to be tested. Glare in these lenses, although some of which are mirrored systems, must also be anticipated.

A1.3.7 ILLUMINANCE METERS

There are various types of illuminance meters that are used in making measurement on front projectors. Handheld illuminance-meter measurement results may be affected by light scattered from the person holding it. Illuminance meters can also be affected by stray light from the room, probably much more than people realize. A full discussion of some of these problems will not be found in this appendix; rather they are included in Chapter 15 Front Projector Metrics because they apply only to that chapter.

A1.3.8 TIME-RESOLVED MEASUREMENTS

In making time-resolved light measurements such as response times, photopic calibration may not be required. However, be cautious about infrared (IR) sensitivity of some non-photopic detectors. The IR emitted from the display may have a very different grayscale than the visible light would indicate. Sensitivity to IR can produce a dc offset which may or may not be important to an accurate measurement. The response time of the LMD is often required to be 1/10 the duration of the event to be measured, preferably less. If the light generated is modulated at a high frequency, it may be necessary to require a response time of the LMD used for temporal measurements to be 1/10 or less of the temporal period of the modulation or change. See the section on Temporal Response Diagnostics (A8) for details on how to check the temporal response capabilities of the LMD used. There are few absolute (repeatable) sources of error in this measurement:

1. Detector non-linearity.
 2. Detector time-base error, e.g., the time-per-division on the oscilloscope is wrong.
 3. Step-response function (SRF) curve affected by too large a measured target.
 4. Detector noise.
 5. Detector drift.
 6. FPD luminance drift.
 7. Superimposed luminance ripple (as with a high-frequency backlight).
 8. Use of linear interpolation on a non-linear SRF curve.
 9. Intrinsic FPD turn-on and turn-off frame-to-frame variations.
- Since (1) and (2) above are normally small, and (3) can be controlled by proper target selection, this measurement should be both accurate and repeatable if the following random (non-repeatable) error sources can be controlled:

A1.3.9 DETECTOR SATURATION

When measuring displays that produce their light by a train of pulses, such as electron-beam scanned phosphors of a CRT or a scanning laser wall display, it is important that the peak of the light pulses not saturate the detector within the LMD. Detector saturation can be determined using the diagnostic for linearity in A3.3 Detector Linearity Diagnostics. If the ratio of light measured with and without a neutral-density filter stays the same independent of the luminance setting of the display screen (whites or grays), then saturation is not a factor. If there is fear of changing the pulse characteristics by changing the gray-level, then the apparent screen luminance can be adjusted using a second neutral-density filter between the LMD and the white screen. By changing the density of the second neutral-density filter you can simulate a change in gray scale without modifying the pulse shape.



A1.3.10 APPEARANCE TO THE EYE VS. THE LMD

The eye has an entrance pupil of less than 10 mm diameter (typically 2 mm to 4 mm, many use 5 mm). Most LMDs have lenses that have considerably larger diameters, 25 mm and larger. It is worth keeping in mind that what the eye sees and what a LMD sees may be somewhat different. From any point on the display surface, the eye and the LMD often subtend very different solid angles, particularly as the LMD gets closer to the display. Sometimes the detail seen by the eye can be integrated out by the LMD. Sometime, this can be particularly noticeable as when comparing a picture using a camera (array detector) with what the eye sees when examining a non-smooth surface. The camera can make the surface appear smoother than it is and any sharp detail behind the surface (such as pixels behind a diffusing screen) may be softened from what the eye sees. There's not much to do about this except to be aware that sometimes stopping down the lens (higher f-number, smaller iris) may make the LMD see more like the eye sees things at a cost of sensitivity.

A2 STRAY-LIGHT MANAGEMENT & VEILING GLARE

Light measurements can be corrupted by stray light in the detector. Such stray light can arise from light reflected within the lens (between the glass surfaces), dirt or dust along the light-ray paths that scatters light, reflections off of stops, the iris, the sides of the lenses, lens defects and bubbles, scratches and digs in the lens surfaces (difficult or impossible to see with the eye), and any other part of the lens-detector system. The manifestation of this stray light is called veiling glare when it is not very noticeable or lens flare when it becomes obvious as streaks, stars, or transparent disks often colored. Veiling glare often refers to the stray light that floods the entire image area and is not as noticeable because of its quasi-uniformity. Veiling glare is particularly corrupting when attempting to measure dark areas on the screen when bright areas are also present on the screen. Even our eyes, although having extraordinary capabilities, can also have glare problems such as when the bright lights of an on-coming automobile cause an obscuration of the road (often this gets worse with age and may be called disability glare), or when looking at a sunset we have difficulty seeing shadow details. The effects of veiling glare are not limited to measurements of black with white in the vicinity. Errors can also be introduced in measuring bright areas and colors. The amount of veiling glare is very dependent upon the optical system used. Errors as high as a few percent in measurements of white have been observed depending upon conditions. Because of glare, serious errors of hundreds even thousands of percent can be introduced into black measurements when white is present on the screen.

There are two regimes that are of interest: Large-area measurements and small-area measurements. Making accurate large-area measurements of luminance is straightforward when a proper mask is employed. Making accurate small-area measurements of dark areas when bright areas are present can be very challenging. We first discuss the large area measurements, and then we will provide some pointers on how one can deal with small-area measurements. Often, we speak of contrast as a metric of interest. There may be metrics that offer a better rendering of the visual perception of the contrast than the contrast ratio.

A2.1 AVOIDING GLARE IN LARGE-AREA MEASUREMENTS

The simplest way to avoid veiling glare is to mask off the region being measured so that most of the light exposed to the lens system is the light being measured. Figure 1 shows a rectangular mask (cut away to show the screen) used to measure the dark green area on an otherwise white screen. The mask is at least 10 % larger than the round area measured by the LMD — the measurement field. However, there are cautions in using masks. We don't want the mask to affect the display being measured. That is, we don't want the mask to reflect light back onto the display, so the measurement is affected by the reflections from the mask—see Fig. 2. A variety of flat, rectangular masks have been used such as black paper, black gloss plastic, black matte plastic (preferred over black gloss plastic for a flat mask used near the screen), black flocked paper (has something like a thin black velvet coating), and black felt. If the display surface is rugged enough to accommodate it, even black masking tape has been used. However, the flat masks are effective especially when they can be placed very near or on the pixel surface. When they must be displaced from the pixel surface, the flat mask can reflect light back onto the display surface that can corrupt the measurement. A displacement of the flat mask from the surface may arise either by a covering glass on the display surface (recessed pixel surface), the measurement system restrictions, or the delicate nature of a prototype display that will not tolerate the mask touching its surface. If a flat mask must be used, black felt fabric is often the best material to use. There also may be another problem in using flat masks directly on the screen: The cooling

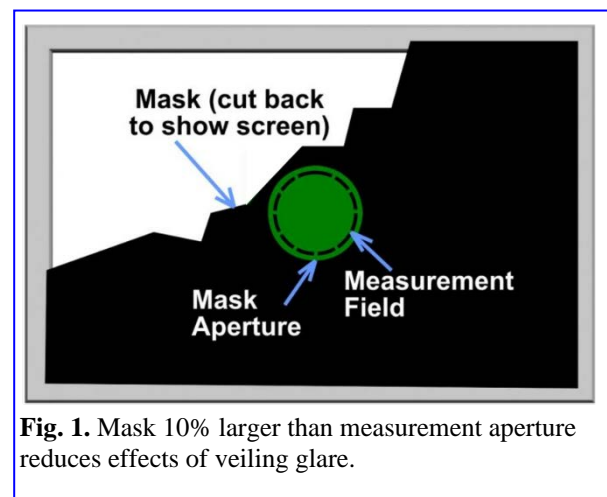


Fig. 1. Mask 10% larger than measurement aperture reduces effects of veiling glare.



properties of the screen may be affected, the screen may get warmer, and its properties may be affected accordingly. To get around some of these problems a method of using a frustum mask is presented below.

A2.1.1 GLOSSY BLACK FRUSTUM MASKS:

A gloss-black frustum (right circular cone with point cut off) mask can also be used to restrict much of the unwanted light from entering the LMD, see Figs. 2, and 3 (see construction specifications below). To avoid light from the rest of the display being reflected onto the viewing area and to avoid the light from other parts of the screen reflecting off the interior of the frustum and into the lens, the apex angle of the frustum should be 90° (45° each side of the optical axis of the LMD and the symmetry axis of the frustum). So that the edge surface of the frustum will not obscure any of the measured area (producing a vignette), the frustum must be placed close enough to the display surface so that the inequality shown in Fig. 3 is satisfied:

$z < z_{\max} = d(s - u) / (w - u)$, where z is the distance of the edge of the aperture of the frustum from the display surface, u is the size of the display surface measured by the LMD, w is the width of the LMD lens aperture (entrance pupil), d is the

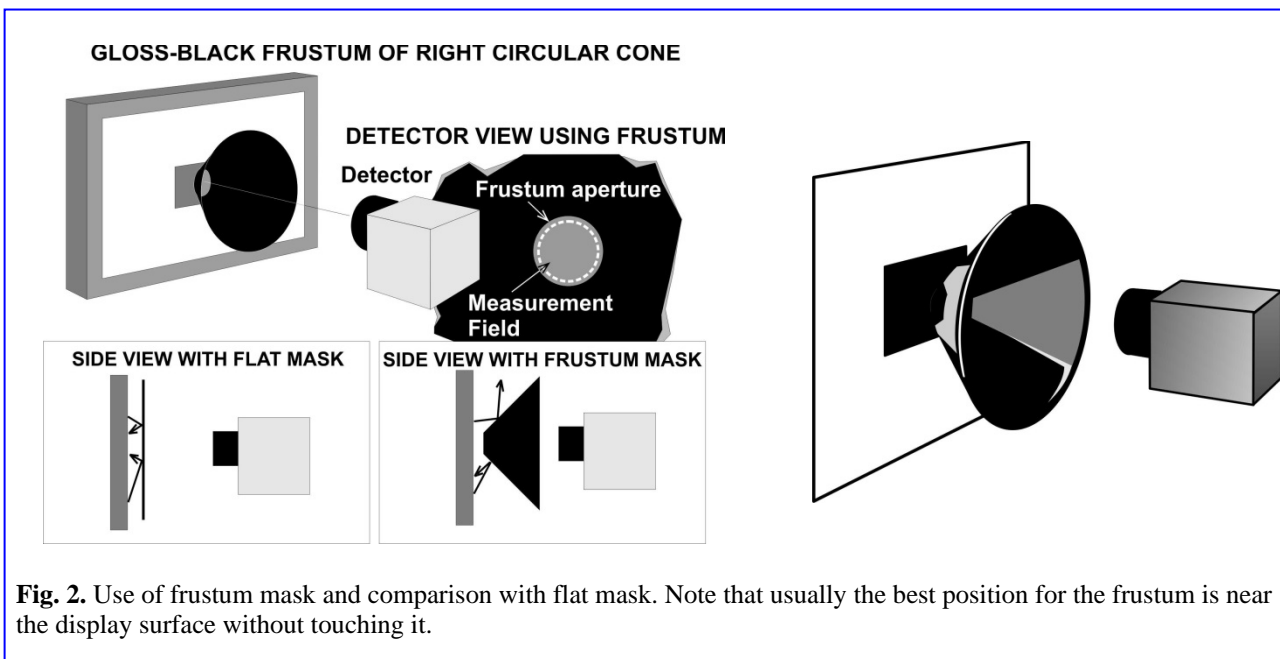


Fig. 2. Use of frustum mask and comparison with flat mask. Note that usually the best position for the frustum is near the display surface without touching it.

distance the LMD lens is from the display surface, and s is the size of the aperture of the frustum. In practice, z will be usually less than the limit expressed by the inequality so that the frustum will not inadvertently obscure any of the area viewed. In fact, the frustum aperture will usually be placed as close to the screen as is practicable. This requirement on z arises from insisting that all light rays from the region viewed by the LMD can enter the LMD. As much as possible, all bright areas on the display should be outside of the region denoted by p in Fig. 3, where $p = [z(s + w)/(d - z)] + s$.

The outer diameter of the frustum should be sufficient to prevent light from the edges of the screen from entering the lens of the LMD. In the case of large displays where it would be impractical to make a single frustum with sufficient outer

diameter, try a second frustum or flat mask where the hole is larger than the diameter of the lens of the LMD. The second mask is nearer the LMD and obscures the large area of the display but permits a clear view of the frustum placed nearer the display through which the measurement is made. Whatever you do, think in terms of how reflections can corrupt the measurement. A tube with a frustum on the end may also be used; further discussion of this apparatus is provided below in A2.1.5 Stray-Light Elimination

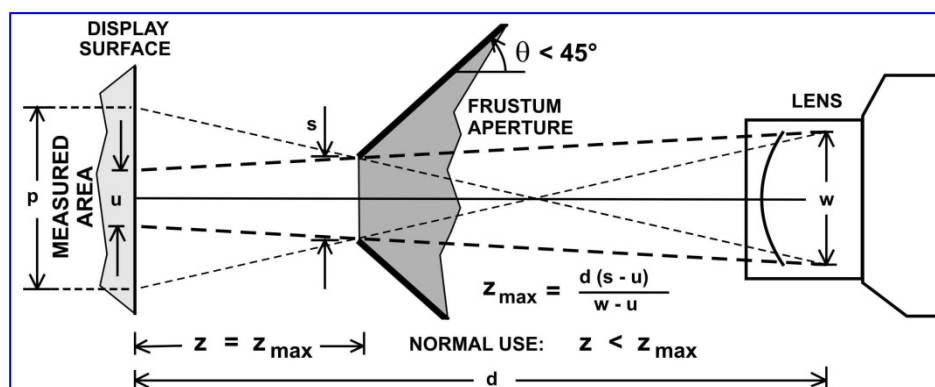


Fig. 3. Use of gloss-black frustum mask to shield the lens of the LMD from bright parts of the display surface.



Tubes (SLETs).

The edge of the frustum nearest the measurement field is never perfect, so some light can scatter from the edge into the LMD as well as back onto the display surface. Additionally, diffraction can contribute to the stray light especially when the frustum aperture diameters get very small, a situation in which the edge scattering may be relatively great. Well-designed frustums have been successfully used with apertures down to 1 mm.

A2.1.2 DIAGNOSTIC FOR FRUSTUM-MASK EFFECTIVENESS

The following is a diagnostic for testing how well the frustum masks eliminate glare.

What this amounts to is a more detailed investigation of the use of the frustum and can be ignored unless you are particularly interested: The success of the addition of the frustum to improving the measurement of contrast can be tested by viewing a gloss-black disk placed on a glass plate at the exit port of a uniform light source, see Fig. 4. The disk should have a diameter of approximately p (-0% , $+20\%$). A comparison of the luminance measurement of the disk with and without the frustum present will provide an indication of the effects of lens flare. (This is similar to the CIE diagnostic mentioned below.) To better understand the effects of the frustum on the measurement, perform the following procedure: The target is brought up to just touch the edge of the frustum, and the luminance L is measured as a function of distance of the target from the edge of the frustum, that is, obtain $L(z)$ for the target disk without changing the distance between the LMD and the frustum. This will provide you with a better understanding of the use of the frustum. The amount of luminance measured when the frustum is at the selected position z_{sel} from the disk provides an upper bound on the minimum luminance that the LMD can measure with this frustum arrangement when it is necessary to measure the luminance of dark areas while bright areas exist on the display surface. This measurement also permits an estimation of a limiting contrast ratio C_{limit} that the system can attempt to measure when light and dark areas coexist on the display surface in proximity such as white areas within a distance $p/2$ of the black measurement area u : $C_{\text{limit}} \cong L_{\text{test}} / L(z_{\text{sel}})$. For the geometry in Fig. 3 the sizes of the umbra u and penumbra p are given by

$$u = \frac{sd - zw}{d - z} \quad \text{and} \quad p = \frac{zw + sd}{d - z}.$$

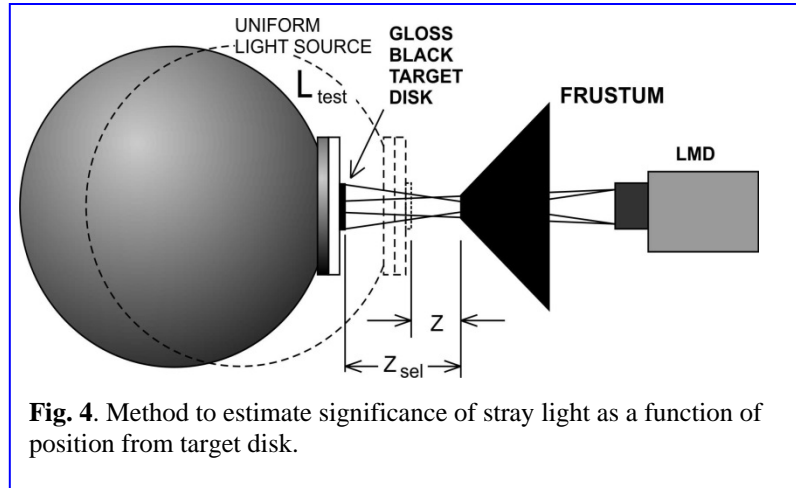


Fig. 4. Method to estimate significance of stray light as a function of position from target disk.

A2.1.3 DIAGNOSTIC FOR LMD GLARE CORRUPTION DETERMINATION

Figure 1 suggests a method of checking how much glare can affect your measurement: Use a gloss-black frustum mask near the screen (or a flat matte-black mask placed on a screen provided your screen will permit such handling) that has an aperture (surrounding the measurement field) that is at least 10 % larger than the measurement field of the LMD (if 10 % is difficult to use, try 20 %; the increased size of the mask aperture makes it a little easier to get the measurement aperture within the mask aperture). Measure the luminance of a white full screen with L_m , and without, L_w , the mask. Provided the area measured is accurately indicated by the viewfinder and that measured area is placed as well as possible at the center of the aperture of the mask, the quantity $(L_w - L_m)/L_m$ expressed in percent is one measure of the glare problems of the LMD for that application. Here L_w is the luminance of the white screen without the mask, and L_m is the luminance of the white screen with the mask in place. In general, the size of the screen should be at least ten times the size of the measurement field, if at all possible. If you wanted to make a reproducible measurement of the glare of a system, limit the size of the screen exposing the LMD without the aperture mask by another large-diameter mask that has a round hole having a diameter of exactly ten measurement-field widths.

To readily see how black measurements can be contaminated, the CIE specifies a somewhat similar measurement to characterize the glare: They call for a uniform light source (such as the exit port of an integrating sphere) with a diameter ten times the measurement aperture. [6] A black gloss light trap (see A13.1.4) with a diameter 10 % larger than the measurement aperture is placed at the center of the light source in such a way that it doesn't change the luminance of the source. A flat piece of black opaque material will often do adequately if the reflections from the lab and the LMD do not affect the



luminance of the black material. The luminance of the uniform source is measured with the trap L_t and without the trap L_s in place. The glare is defined as L_t/L_s and can be expressed in percent. (Note that if you are using a uniform source, the luminance of the source may change with and without the trap in place. If the change is not trivial, then an adjustment in the luminance levels may be needed to compensate accordingly.)

The differences between the two glare diagnostic methods are that in the first method above the luminance levels measured and compared are all approximately the same level; whereas with the CIE method the amount of glare is measured directly, and it assumes that the LMD is adequate for the much smaller luminance measurement. Conversely, our method prescribed above is only useful for LMDs that have sufficient precision so that the difference $L_w - L_m$ is meaningful.

A2.1.4 FRUSTUM CONSTRUCTION

A frustum can easily be constructed from thin black vinyl plastic with a gloss surface on each side, see Fig. 5. Good results can be obtained with vinyl plastic 0.25 mm (0.010 in) thick (it's easy to cut with scissors or a knife). Given the size of the aperture $d_1 = 2r_1$, the outer diameter of the frustum $d_2 = 2r_2$, and the apex angle β related to its complementary angle ϕ by $\phi + \beta/2 = \pi/2$ or $\beta = \pi - 2\phi$, we want to know how to cut the proper shape from a flat sheet of plastic. We need the inner flat radius R_1 , the outer flat radius R_2 , and the flat-angle subtended θ . We can express several relationships: The length of the side can be expressed in terms of the flat radii $w = R_2 - R_1$, which can also be expressed in terms of the assembled radii $w \cos \phi = r_2 - r_1$. The circumferences can be expressed in terms of both types of radii: $C_1 = 2\pi r_1 = R_1 \theta$ and $C_2 = 2\pi r_2 = R_2 \theta$. The simplest expressions for R_1 , R_2 , and θ are:

$$R_1 = \frac{r_1}{\cos \phi}, \quad R_2 = \frac{r_2}{\cos \phi}, \quad \theta = 2\pi \cos \phi;$$

$$\text{and for } \phi = 45^\circ, \cos \phi = 1/\sqrt{2},$$

$$R_1 = \sqrt{2} r_1, \quad R_2 = \sqrt{2} r_2, \quad \theta = \pi\sqrt{2},$$

with assembled frustum radii r_1 and r_2 specified. When cutting the sheet, use scissors or a knife to assure that the edges are also at 45° to the display surface when the frustum is assembled.

The straight ends of the cutout piece are butted together to make the frustum. There are several ways to secure the edges together. One way is to clamp the butted edges together flat on a table (with the clamp holding the edges together at the middle of the straight edges). Place a small amount of quick-hardening epoxy over the exposed butted edges to hold them together. After it hardens, remove the clamp and epoxy a narrow piece of the plastic along the butted edges on the inside of the frustum to seal any light leaks from small gaps. The clamp may be useful to hold the strip in place until the epoxy is secure. Be careful not to epoxy the frustum to the table (you can use a non-stick surface like polyethylene or polytetrafluoroethylene [PTFE]). It may take a little compression of the frustum (bending or squishing it) in order to provide a circular hole. A series of frustums can be made that are small, with d_1 from 5 mm to 20 mm or more and d_2 approximately 60 mm. These will fit in a larger frustum with d_1 of 50 mm and d_2 as large as needed to obscure light from the display onto the LMD lens or aperture. You can use a small piece of black tape on the inside of the larger frustum to secure the smaller frustum within the larger.

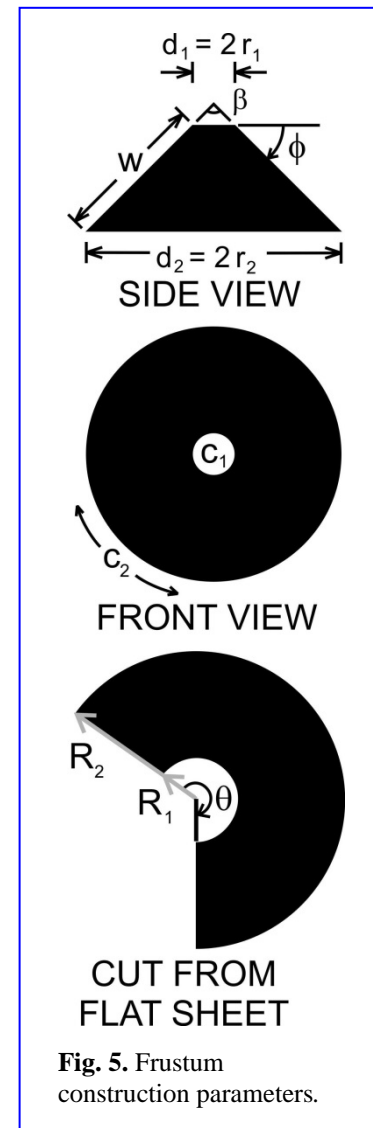


Fig. 5. Frustum construction parameters.



A2.1.5 STRAY-LIGHT-ELIMINATION TUBES (SLETs)

Now that we know how to build frusta, we can use them and combine them to provide good control of stray light. There are at least two kinds of SLETs: A SLET used with a detector that has a lens such as a luminance meter, and a SLET that is used with a bare detector without a lens such as an illuminance meter or filtered photodiode.

A. SLET for Detector with a Lens: The simplest SLET for a detector that has a lens such as a luminance meter is a matte-black tube (interior and usually exterior) with a gloss-black frustum on the end, where the aperture of the frustum is almost touching the region being measured—see Fig. 6. The tube is long enough so that no light from the display directly hits the detector lens from outside of the tube. However, sometimes it is necessary to wrap the gap between the tube end and the lens with black felt or cloth to prevent stray light (as from the room) that hits the front of the detector from making contributions to the results. Without the tube we would need a very large frustum, which is usually rather impractical to build and to manage in the lab. The tube could have a gloss black interior, but then we would need a baffle, one frustum, or multiple interior frusta to prevent bright reflections off the inner wall from affecting the result. Because the detector has a lens it already is most sensitive to the light in the measurement field. The small amount of light scattering off the interior matte-black surface is usually inconsequential. However, if the light hitting the walls is extremely bright, it can affect the measurement. In such a case another interior frustum must be added to prevent the detector from seeing that bright light. Another way to make the interior walls blacker is to use a black fabric such as black felt.

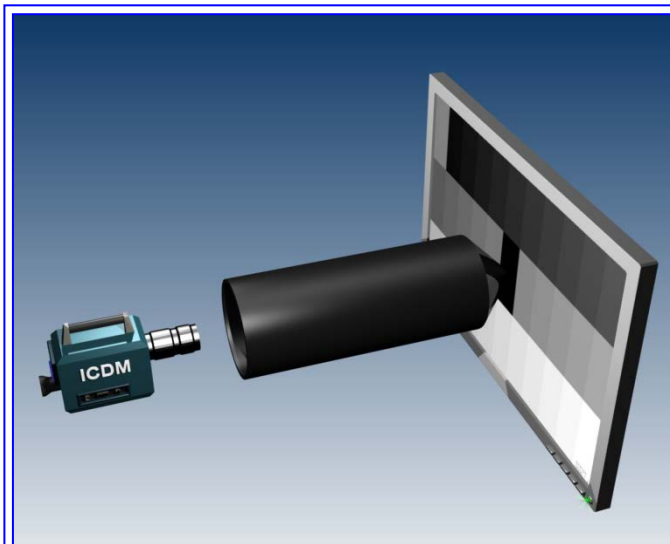


Fig. 6. SLET for LMDs with lenses.

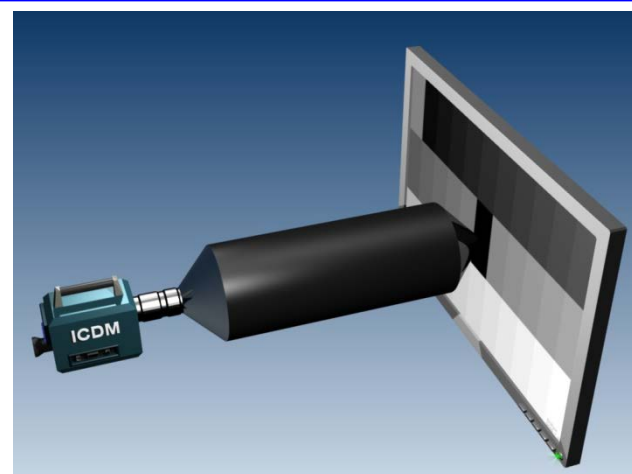


Fig. 7. SLET for LMDs with lenses—version with frusta on each end (lens-end frustum fits the lens).

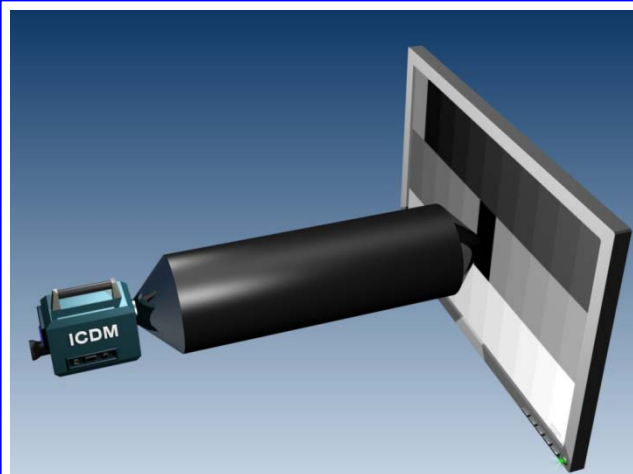


Fig. 8. SLET for LMDs with lenses—version with frusta on each end (lens-end frustum encompasses the lens).

Instead of wrapping the gap between the lens and the tube end with black cloth, another frustum can be added to the lens side of the tube to prevent stray light from reflecting off the lens or the front of the detector then off the screen and back into the detector corrupting the measurement result. See Figs 7 and 8. Especially when we have a large screen and are trying to measure a small black box on an otherwise white screen, quite a bit of light can be reflected about the room—even a good darkroom—and illuminate the front of the detector and the lens so that the “black” measurement becomes mostly the reflected light from the LMD off the screen and not the true black of the screen.

B. SLET for Detector without a Lens: Illuminance meters and open photodiodes or filtered photodiodes do not have a lens to focus most of their sensitivity in a certain direction; they can be affected by light from a large area. In the case of illuminance meters, they can be designed to collect light from the entire hemisphere. If it is necessary to limit the stray light from the surround as in making illuminance measurements on a projector in a high-ambient-light room, then a SLET may be required. A SLET designed for such measurements can be made from a tube with a gloss-black interior and with several gloss-black frusta inside to prevent light that you don’t want from contributing to the measurement result. In Fig. 9



we show a gloss-black interior SLET for illuminance measurements where a domed illuminance head is used. It employs four main frusta and a wide frustum at the detector end. The aperture of the front frustum can be smaller than the ones nearer the detector. Every surface inside the SLET is smooth and gloss black.

In Fig. 10 we show a simplified two-frustum SLET for making illuminance or flux measurements in a certain direction where the illuminance head is recessed in the body of the meter. In such a case the placement of the two frusta are very important to prevent stray light from reaching the detector.

Often, we place our eye where the detector should be and then move the frusta while aiming the tube at a large bright light (such as an overhead room light) so that we don't see any direct reflections of the light while peering around the interior of the tube.

C. SLET for Detector with a Lens at a

Distance: Suppose we have a detector with a lens that is attempting to measure a dark object like a black box with brighter areas of the screen surrounding it as in Figs. 6-8, but we want to include the ambient from the surround in the measurement of the dark object. An example of this is in the next section on low-luminance measurements where we want to measure a white standard at the center of the screen with the screen showing some color Q . We can use either kind of SLET to do this provided we are careful. Figure 11 shows a SLET for a detector with a lens measuring a black area on a screen that is subjected to ambient illumination. The interior of the SLET can be matte black or gloss black depending upon the levels of ambient illumination and how much of an effect they produce within the SLET. If the interior of the SLET is gloss black, then other interior frusta must be used to eliminate the stray light. The problem with this use of the SLET is the vignette created by the out-of-focus frusta edge nearest the display. It is imperative that this fuzzy edge does not interfere with the measurement field of the detector or that the edge of any frustum doesn't obstruct any ray that contributes to the measurement result (see considerations in § A2.1.1. Black Glossy Frustum Masks). The measurement field must be centered within a uniform area inside the vignette from the out-of-focus frustum edge. In this case where the SLET is removed a distance from the display, frusta are probably not required, but simple flat matte black masks on the end of the tube will very likely do just as well.

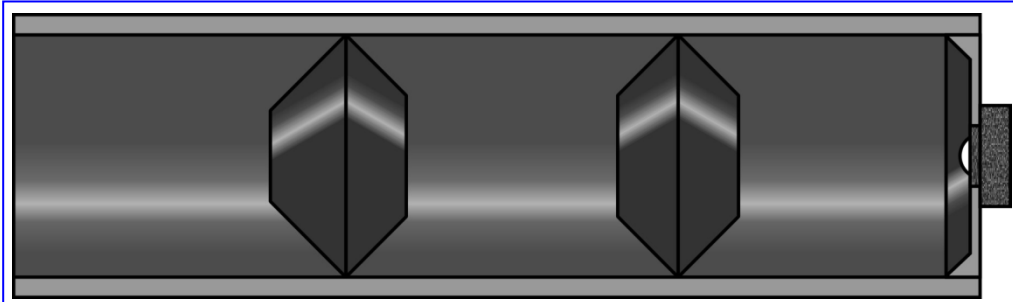


Fig. 9. SLET for illuminance meters with a dome that sticks out from the body of the meter. All interior surfaces are gloss black.

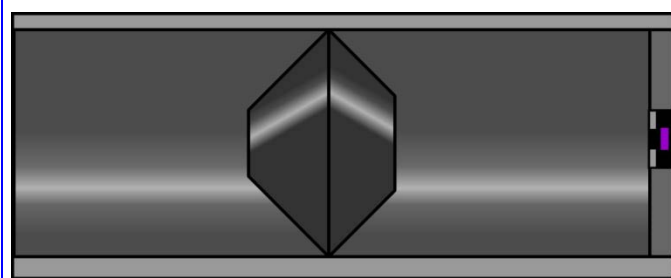


Fig. 10. SLET for illuminance meters with the detection element shielded by the body of the meter. All interior surfaces are gloss black.

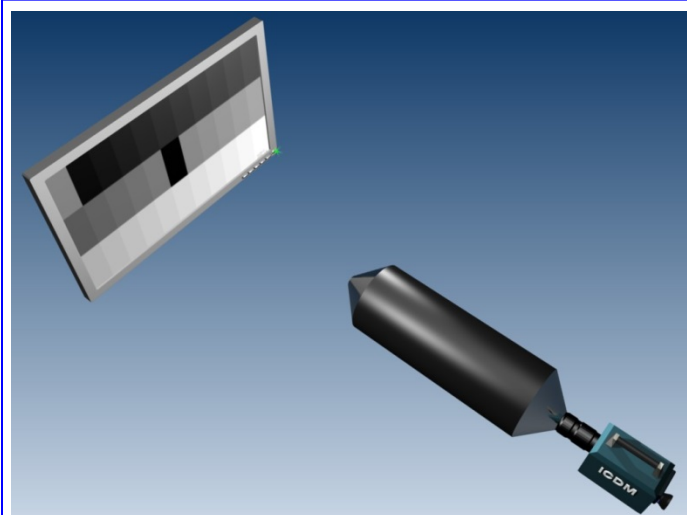


Fig. 11. One example of a SLET for a detector with lens but allowing ambient light from room to affect the dark area to be measured. It is important to be sure that any hole edge of the SLET does not obstruct any ray that contributes to the measurement result.



A2.1.6 CORRECTING FOR GLARE WITH REPLICA MASKS

The use of a replica mask is an approximate method to account for glare in the detector—it is not perfect. To do such a thing correctly would require convolution/deconvolution techniques with a knowledge of the point-spread-function of the detector—a very difficult task. The replica-mask method is useful for when an aperture or frustum mask is not feasible.

DANGER: SOME DISPLAY SURFACES CANNOT BE TOUCHED. BE CAREFUL! BE SURE YOU CAN TOUCH THE SCREEN BEFORE PLACING ANYTHING ON THE SCREEN SURFACE. See part (B) for obtaining a correction for use with a delicate (untouchable) surface.

A. Rugged Display Surface: Should an aperture or frustum mask not be convenient to use, it is possible to approximately correct for the glare by making a black-opaque mask that is the same size as the area of black intended to be measured—a replica mask—such as a black rectangle in a checkerboard pattern. See Fig. 12. There are several cautions: (1) Light from the room must not light up the mask. (2) If a gloss-black material is used, it is important that no equipment lights or illuminated room areas are reflected off the gloss surface into the detector. It may be useful to tilt the glossy mask slightly, so the specular reflection is looking into a very black area of the room. (3) It is very important to avoid back reflections from an emissive display off the detector and back onto the replica. It may be necessary to use a long-focal-length lens (and extension tubes when using a camera) to keep the detector away from the replica (500 mm will probably not be enough). (4) If a matte-black material is used for the replica, then the darkroom must be of a high quality so that no measurable light falls back on the replica either from the room, items in the room, or the detector back reflections. And, finally, (5) avoid measuring near the edges of the replica; always try to measure at the center of the replica—this may require using a smaller measurement field that normally desired; sometimes an array detector is employed for these measurements.

Suppose we have a checkerboard as in Fig. 12. Let L_g be the luminance of the black-opaque mask when covering the black region to be measured. This L_g is approximately the luminance of the veiling glare contamination (“g” for glare). Let L_d be the luminance of the black-pixel region (“d” for dark) without the mask and let L_h be the luminance of the surrounding white pixel region (“h” for high). The corrected white measurement is

$$L_w = L_h - L_g, \quad (1)$$

which will usually be a small correction. The corrected black measurement is

$$L_b = L_d - L_g. \quad (2)$$

An approximate measure of the true contrast of white to black is

$$C = L_w / L_b = (L_h - L_g) / (L_d - L_g). \quad (3)$$

This is not necessarily a very precise way to measure the true black value since the localized glare in the region of the covering mask is usually not uniform across the mask—that is why we measure at the center of the replica. The frustum aperture mask is a much better way to make a high-contrast large-area measurement when it can be used.

B. Delicate Display Surface: Suppose the display surface, DUT (display under test), is delicate so that you cannot touch the surface, much less secure a small target on the screen. You might try to place the replica mask a few millimeters in front of the display but not touching the display, perhaps suspending it by fine threads or wires. The problem might be that you will not be able to focus well on both the replica mask and the pixel screen if you are using an array detector with a large-aperture lens far away. If you don’t dare to use anything near the screen for fear of harming the surface, you can try to use a substitute display of the same size and pattern to be measured. The detector-display geometry must be the same as with the DUT. We can then obtain a correction to the black measurement to be performed on the DUT. Let the white substitute-display luminance surrounding the mask parts be L_h' , and the luminance of the center of the black mask on the substitute display be L_g' . The glare luminance that would have been obtained on the DUT if we could have placed a replica mask on its screen is

$$L_g = L_h L_g' / L_h'. \quad (4)$$

The analysis will then proceed as in the above section (A).

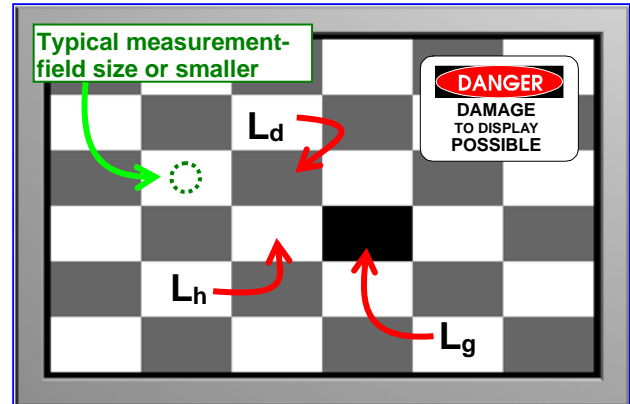


Fig. 12. A checkerboard pattern is measured using a replica mask. The black pixel rectangle to be measured is above and to the left (L_d). The replica mask of the same size is the rectangle beneath and to the right of center (L_d). The white (L_h) is below the dark (L_d).



A2.2 ACCOUNTING FOR GLARE IN SMALL-AREA MEASUREMENTS



DANGER: SOME DISPLAY SURFACES CANNOT BE TOUCHED WITHOUT SERIOUS DAMAGE. BE CAREFUL! BE SURE YOU MAY TOUCH THE SCREEN BEFORE PLACING ANYTHING ON THE SCREEN SURFACE.

For measuring small areas on the screen, it may not be possible to employ a frustum mask as described above for two main reasons: (1) The imperfect edge of the mask reflects too much light into the lens and back onto the screen (the ratio of the circumference to the area of a circle, $2/r$, gets larger as the radius gets smaller), and (2) for very small holes diffraction can be sufficient to corrupt the measurement. Not only luminance measurements can be affected by these problems. If there are multiple colors on the screen, then they can be similarly mixed to some extent by glare and reflections. This can affect the accurate measurements of chromaticity.

Keep in mind that glare generated within the optical system is not the only source of corruption of black (and white for that matter). Moderate magnifications are often needed for measuring—at the pixel level—individual black characters or lines on an otherwise white screen. Such optical systems may require a lens and holder in close proximity to the area of the display being measured. In such cases there is a high probability that the instrumentation can reflect light from the white areas of the screen back onto the screen thereby especially corrupting the black measurements. It is advisable to avoid detector proximity and use a long-focal-length lens (with extension tubes if necessary) to be sure that the detector is far away from the screen.

A2.2.1 REPLICA MASKS AND DIAGNOSTICS

Figure 13 illustrates the concept of an opaque black replica mask and a filter replica mask for a diagnostic tool. The exploded area shows the pixel detail of the rectangular area containing three squares. It could be a high-magnification image obtained from a camera (array detector): The bottom center square is a 4×4 pixel area where the pixels are black—this is what we want to measure accurately. The top left square is a piece of black mask material cut to the same size as the 4×4 pixel area—a replica of the black area on the screen. The top right square is also a replica mask the same size as the 4×4 pixel area, but it is made from a clear neutral-density (gray) filter material having a density of 1.0 or greater (transmission of 1 % or less) and is placed over a white area of the screen. We measure the white pixel area S_h , and the centers of each square: S_g for the opaque mask, S_f for the filter, and S_d for the black (dark) pixels. If possible, try to measure increments of full pixels. When using an array detector, experience seems to favor having a sufficient magnification so that 20 or more *detector* pixels span the minimum size of the black area, in this case the width of a 4×4 pixel square (try to get 10 to 20 detector pixels per display pixel if possible). The presence of the filter serves a check, a diagnostic. If you cannot measure the attenuation of a filter properly, then your measurement using the mask will be in question.

Admittedly, it sometimes is not easy to cut either the opaque mask material or the plastic filter material to the same size as the pixel area being measured, particularly if the area is small. However, every attempt should be made to cut the replica masks and filters to within 10 % of the smallest linear dimension of the black pixel area. The idea behind the replica mask is that whatever light is measured in the replica mask is due to glare within the imaging system—the replica mask should, ideally, be absolutely black, and it is not because of glare. Since the **size and shape** of the replica mask is the same as the black-pixel area being measured, then it would seem reasonable to expect that the glare measured in the replica mask is the same as

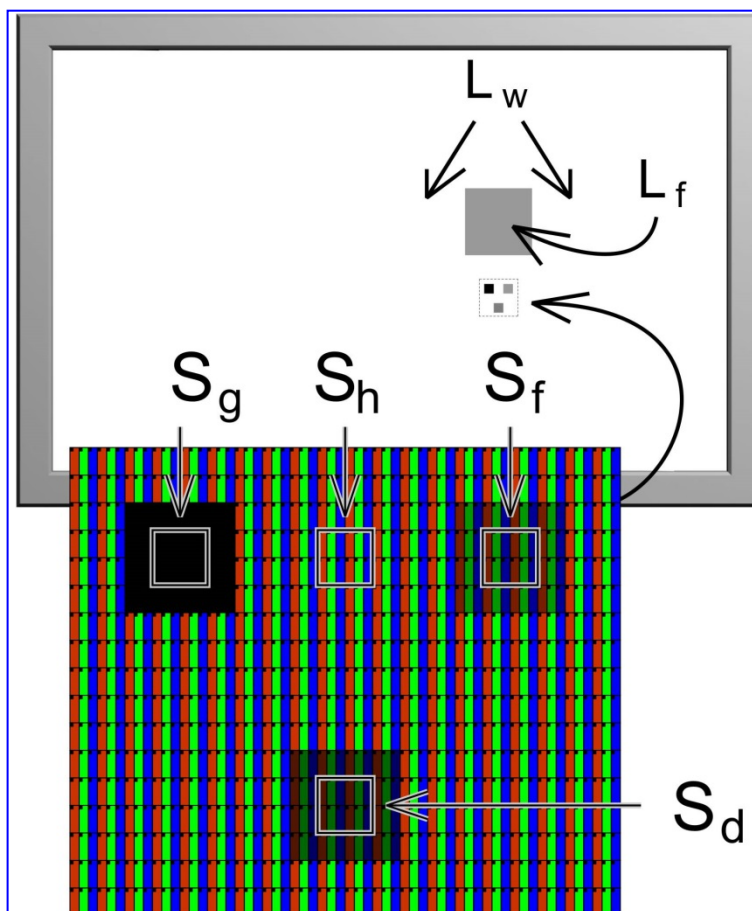


Fig. 13. Use of plastic filter material to serve as a diagnostic to determine if replica mask technique is working properly.



the glare added to the black pixel area. It should be remembered that the replica mask (and filter) should be **separated** a distance from the black area so that they don't interfere significantly with each other by changing the glare characteristics of the imaging system. How far they should be separated is hard to say, but they should be separated at least by two full widths of the minimum size of the black region to be measured.

The material used for the replica mask can be important. Gloss-black plastic works well provided that the glossy surface is not reflecting any light from surrounding objects into the lens. Since the filter also has a glossy surface, reflections must be controlled as much as possible. Any unwanted reflections off of these glossy surfaces are usually not readily visible to the eye, but they may show up as an inaccurate measurement of the transmission of the filter replica mask. There is a problem with using plastic filter material. Most such materials have a non-trivial **temperature coefficient**. Thus, the filter material must be calibrated for the temperature conditions of the screen. To solve this problem, use a large piece of filter material placed on the screen that can be measured with a LMD and a frustum mask (shown above the inset area in Fig. 13). After the filter material has warmed up to the display surface temperature, measure the luminance of the filter L_f . Then measure the luminance of the screen on each side of the filter and average those results L_w . The **transmission** of the filter material is then $\tau = L_f/L_w$. (It is also possible to lift up the filter material and measure L_w in the same place as where the filter was measured. In such a case be sure the measure the filter while on the screen first so that the filter is at the proper temperature.) When you measure

the transmission of the filter material used for the small area replica mask $\tau' = (S_f - S_g)/(S_h - S_g)$ and you obtain a value close to τ (within 5 % is good), then you may feel confident of your technique, and proceed with the glare correction of black. The **black** level is determined by $S_b = S_d - S_g$. The **white** level is $S_w = S_h - S_g$. And the **contrast** is $C = S_w/S_b$. This corrected contrast should be significantly larger than the uncorrected contrast S_h/S_d . To obtain luminance values for the black and white measurements, the LMD must be calibrated for luminance measurements—see A9 Array-Detector Measurements. However, obtaining the correct T value may not always indicate a valid measurement method particularly when the black levels being measured results in a very small signal comparable to the noise in the detector. We may end up subtracting noisy signals rather than legitimate signals and accidentally obtain τ . In such cases it is best to increase the exposures to compensate accordingly and properly scale the longer-exposure signals to the signal levels used in measuring the white region.

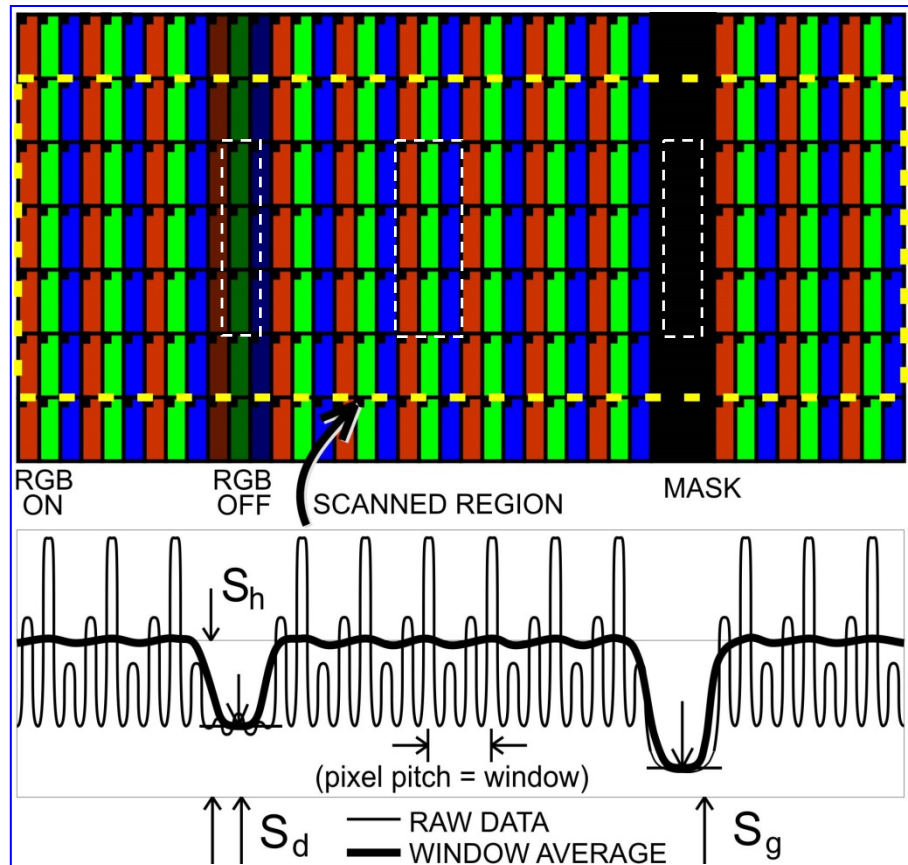


Fig. 14. Hypothetical high-magnification image of black pixel line on white pixel background with an ideal black-opaque mask placed directly upon the pixel surface. The yellow dashed region is the scanned area if a scanned image is used. The white dashed boxes illustrate the areas selected if just area measurements are made. This is an ideal situation to illustrate what we are attempting to do. Do not attempt to touch the screen surface unless you are sure it is rugged enough to permit such rough handling.

A2.2.2 LINE REPLICA MASKS ON RUGGED SURFACES

The methods for correcting for veiling glare discussed here are only approximations to attempt to account for the effects of glare. It certainly provides a better measurement than would be obtained without any correction at all. In the previous section we handled the general case. Here we will assume we are trying to measure the luminance of single pixel line. In Fig. 14 we simulate a high magnification image of a black line on a white background where the individual pixels are resolved. In this



hypothetical situation, let's assume that we can put a line replica mask directly on the pixel surface. A black opaque mask of width equal to the pixel pitch is placed over a column of pixels no closer than three columns away. An integral number of rows of pixels are scanned either by a scanning device or an array detector to produce a luminance profile. Then the luminance profile may be evaluated by means of a moving-window average (see B18 Digital Filtering by Moving-Window Average) where the averaging window is the same width as the pixel pitch in the luminance profile, or the luminances may be evaluated by attempting to measure an internal region or area of the black line and pixel. When making area measurements the white pixel(s) must be measured in integral number of pixels in their entirety. The resulting measurements have an average value associated with the white pixels S_h , an average valley level associated with the black line S_d , and the level of the veiling glare S_g associated with the black-opaque mask. The corrected white is $S_w = S_h - S_g$, and the corrected black is $S_b = S_d - S_g$. Then, for example, the contrast ratio can be better estimated by $C = S_w / S_b$. One problem with this method is that we cannot always get the mask close enough to the pixel surface so that the mask and the pixels are both in focus in our array detector. This happens when there is a thick covering over the pixel surface. The other problem is that the surface of the display may be delicate so that we cannot touch it with anything, even our little mask—we handle that in the next section.

If possible, it is useful to check your results by providing a filter material the same size as the opaque mask and use the method outlined in the previous section to measure the transmission. However, this will usually be difficult or impossible to do because of the small size of the pixel, which can be smaller than the thickness of the filter material used. You can attempt to get some idea by cutting a sliver of filter material with a very narrow angle using a scissors. At some place along the sliver the thickness might be the same as the pixel pitch. Try to arrange for sufficient magnification that 20 *detector* pixels or more are used across the width of the line.

The black mask at the thickness of the pixel may be made by cutting long tapered lengths of the mask material with a razor knife or scissors. The tapered mask is then positioned longitudinally along the pixel line until its width is the same as a pixel width at the position of the measurement.

One of the problems with this method is that the amount of veiling glare is not constant across the mask. As we get closer to the white-black boundary, we will find that the glare increases. It will be a minimum at the center of the black area. However, when you try this method out, you may well find that the amount of veiling glare corruption is substantial (much more than most think). The correction you make will be vastly superior to using measurements that don't attempt to account for glare. For example, suppose we measure the uncorrected black and white levels to be (in CCD counts from a photopic CCD camera) $S_h = 12000$ and $S_d = 2500$. We'd naively calculate the contrast to be $C = S_h / S_d = 4.8$. If we attempt to account for glare and find that $S_g = 1500$ and $S_s = 16000$ using the simulated display. Then the correction is $S_h S_g / S_i = 1125$, and a better approximation to the contrast is $C' = S_w / S_b = 10875 / 1375 = 7.9$, which is quite different from C . Whether or not the eye can appreciate that change in contrast is really not the point of all this. What we need to do is to provide as accurate a measurement as possible so that any study of the significance of small area contrasts is based on good metrology.

A2.2.3 DELICATE UNTOUCHABLE SCREENS

We want to attempt to simulate the situation in Fig. 14 as best we can. We measure the black corruption in the line replica mask and apply that correction to the black area on the DUT. One way to approximately do this is to create an illuminated surface, a simulated screen, that is the roughly the same size as the screen we are trying to measure. This simulated screen can be made in several ways. It can be a rugged display approximately the same size as the DUT, it may be a piece of glass placed in front of but not touching the screen, a backlight by itself, a large box with an illuminated white interior and a rectangle cut in its side the size of the DUT surface, and so forth. The surface should be relatively uniform to the eye. The exact required size of the simulated screen depends upon the apparatus used. Certainly, if the simulated screen is the same size (within $\pm 10\%$ or so) as the screen to be measured, there will likely be no size problem. On the other hand, if the apparatus is essentially not affected by light beyond 20° from its optical axis, then the simulated screen need only subtend a cone with a 40° apex angle. Once the simulated screen is made, place a line replica mask on that surface that has the width of the pixel pitch. In practice, the replica mask should be as close as possible to the pixel pitch. An acceptable mask material will have to be determined for each apparatus and configuration—be careful of reflections from the room and off the detector lens. Clearly, a line replica mask will be easier to create to simulate a line than a character-shaped replica mask to simulate a character. The array detector then measures the across the ideal black line on the white surface obtaining a white level S_s of the simulated screen and a black level S_g that is essentially the veiling glare corruption. Then the DUT can be measured similarly obtaining a white level S_h that is the average of the white area and a measurement of the black area S_d . The equivalent correction for the veiling glare adjusted for the actual screen luminance is $S_h S_g / S_s$. The corrected white is $S_w = S_h (1 - S_g / S_s)$, and the corrected black is $S_b = S_d - S_h S_g / S_s$. Again, this is an approximation for the veiling glare corruption.



A2.2.4 RUGGED SCREENS THAT CAN BE TOUCHED



DANGER! BE SURE THAT YOUR SCREEN SURFACE IS DESIGNED TO BE TREATED ROUGHLY BEFORE ATTEMPTING TO ATTACH ANYTHING TO THE SCREEN SURFACE.

Obviously, the above method for delicate surfaces will also work for rugged screens. However, the rugged screen offers more possibilities. Temporarily attach a one-pixel-pitch-wide strip mask to the surface of the screen (if the screen will allow it, tape might be used), and align it with a column of pixels as shown in Fig. 14. View the mask and black pixel line in the LMD. If the mask and the pixel surface are both in focus (the lens system has a sufficiently large enough depth of field to include the pixel surface and the mask on the cover above the pixel surface) proceed as if it were the ideal case in a) above. However, if both the pixel surface and the mask is not in focus, then data will have to be obtained with the pixel surface in focus and then with the mask in focus separately. When the pixel surface is in focus, we obtain the average white level S_h surrounding the line and the black level S_d of the line, both uncorrected values. When the mask is in focus, we obtain the veiling glare corruption S_g and the average white level (again made with a running window average where applicable) S_s where the background pixels are now out of focus. The correction is now $S_h S_g / S_s$, the corrected white is $S_w = S_h (1 - S_g / S_s)$, the corrected black is $S_b = S_d - S_h S_g / S_s$. Then, for example, the contrast will be approximated with $C = S_w / S_b$.

A3 LOW-LUMINANCE MEASUREMENTS

In the measurement of very small luminance levels there are two problems: (1) the effects of the room, and (2) the capability of the measurement instrument—can it accurately measure low-luminance levels? We supply two measurement methods to answer these questions. The effects of the room and objects within the room are measured in A3.1 Ambient Offset Luminance. Our ability to accurately measure low-luminance levels is quantified in A3.2 Low-Luminance Calibration, Diagnostics, & Linearity.

A3.1 AMBIENT OFFSET LUMINANCE

ALIAS: ambient luminance correction technique.

DESCRIPTION: Measuring the ambient offset luminance as preparation of the darkroom facilities. **Symbol:** L_{AO} ; **Unit:** cd/m^2

APPLICATION: In principle this measurement method is for all luminance measurements, but the lower luminance level to be measured the more important it is. It is definitely a good way to examine the quality of the darkroom being used.

SETUP: Darkroom conditions are obtained by:

1. Reducing and preferably eliminating the luminous output from ALL sources of light (luminaries, displays, control lights, etc.) in the room and by making the room light proof to exterior light sources.
2. All surfaces of the room (walls, floor and ceiling) and all equipment (furniture, fixtures and instruments) in the room must have a diffuse texture and very dark colors, preferably black.
3. The portion of the light output from the object under test, that is not part of the measurement shall be controlled and kept away from the measurement area and directions. Shielding, apertures (frusta and SLETs—see the previous section) and black cloth are very useful in any darkroom.
4. The amount of absorbed light is proportional to $(1 - \rho_{\text{darkroom}})$ and the surface area (walls or/and shielding, ceiling and floor) of the darkroom. A larger darkroom is better than a small darkroom.
5. If there is a computer with a monitor in the room, you may want to consider covering the monitor with black cloth during measurements if it cannot be readily controlled to black or easily turned off.

PROCEDURE: This procedure is intended to facilitate a correction for the ambient luminance present in the darkroom that corrupts a luminance measurement of the display. The source of this ambient luminance is stray light from instrumentation within the darkroom and light scattered from the display when powered on. The following nomenclature is used in the analysis:

L'_Q is the luminance measured on the display with the ambient luminance contamination included, where Q denotes the state of the display: off, W, K, etc.

$L_{\text{std-}Q}$ is the luminance measured on the diffuse white standard with Q denoting the display's state.

L_{AQ} is the true ambient offset luminance disturbance present and which we want to eliminate.

L_Q is the true luminance that we want to measure.

ρ_{std} is the diffuse reflectance of the white standard (8° diffuse or diffuse 8°).

ρ_{display} is the diffuse reflectance of the display (8° diffuse or diffuse 8°).

We will show an example of this procedure for a black display: $Q = K$. This method can be applied for any screen color Q from white to black in order to assess the quality of the darkroom. However, whenever the screen emits light, care must be



taken to assure that the measurement of the luminance of the white standard is not corrupted by glare from the screen (this can be accomplished by using a SLET, see the above § A2.1.5). We will cover the black measurement here. The black measurement is most important because any ambient luminance contamination can dramatically affect a black luminance measurement result.

1. If the reflectances have been measured, then proceed to 5.
2. Make sure the display is off.
3. Measure the luminance L_{Aoff} of the display. (Assumes model: $L_{\text{Aoff}} = \rho_{\text{display}} E_{\text{off}}/\pi$.) This is the lowest and most difficult luminance to be measured.
4. Place the diffuse white standard in front of the display and measure the luminance $L_{\text{std-off}}$ of the diffuse white standard. (Assumes model $L_{\text{std-off}} = \rho_{\text{std}} E_{\text{off}}/\pi$.)
5. Calculate the factor

$$F = \rho_{\text{std}} / \rho_{\text{display}} = L_{\text{std-off}} / L_{\text{Aoff}}. \quad (1)$$

6. Turn on the display (use black full screen and allow a proper warm-up period) and measure the luminance L_{stdK} of the diffuse white standard. Note that if the display is absolutely black (no light when exhibiting a full black screen), then this luminance L_{stdK} will be the same as $L_{\text{std-off}}$ because the display emits no light for an absolutely black screen.

ANALYSIS: The correction for the ambient luminance is calculated according to:

$$L_{\text{AK}} = L_{\text{stdK}} / F, \quad (2)$$

$$L_{\text{AK}} = L_{\text{Aoff}} L_{\text{stdK}} / L_{\text{std-off}}. \quad (3)$$

L_{AK} should be less than 1 % —hopefully much less—of the luminance level to be measured, otherwise a carefully inspection of the darkroom condition will be useful in order to reduce the ambient luminance. The true luminance L'_{K} for the displayed black is

$$L_{\text{K}} = L'_{\text{K}} - L_{\text{AK}}, \quad (4)$$

where we have subtracted the ambient offset luminance from the measured black luminance.

REPORTING: Report the ambient offset luminance L_{AK} for the black screen to at least two and no more than three significant figures

COMMENTS: (1) **Luminance Meter Quality:** The value of this measurement depends heavily upon the quality of the luminance meter and its calibration. It is preferable if the luminance meter is calibrated at the luminance levels to be measured or is verified to have sufficient linearity to cover this level. (2) **Darkroom Quality Evaluation:** The quality of the darkroom can be evaluated with the following data: (a) If $L_{\text{std-off}}$ is low, then we have a low ambient light level in the darkroom. (b) If the ratio $L_{\text{stdK}} / L_{\text{std-off}}$ is small, then we have good adsorption and stray-light control in the darkroom. (3) **Extension to Other Colors Q :** This analysis can be performed with the screen exhibiting any color Q from white ($Q = W$) to black by substituting the selected color Q for the “K” in the above equations and using a screen exhibiting color Q instead of black.

A3.2 LOW LUMINANCE CALIBRATION, DIAGNOSTICS, & LINEARITY

DESCRIPTION: We test and calibrate a LMD for low-luminance level measurements. A typical system consists of a quartz-tungsten-halogen (QTH) lamp, a $V(\lambda)$ detector (separate from the LMD) and a standard white reference plate of known reflectance properties; all of this is in a very low-ambient-light environment. Several methods to calibrate, diagnose, and check the linearity of a LMD are also suggested **Unit:** cd/m². **Symbol:** L .

SETUP: The general arrangement of such a system is shown in Fig. 1. The light source is a stable QTH lamp (or equivalent) for which the power is often 10 W. At an appropriate distance (e.g., 3.5 m) place a translation stage upon which are set a $V(\lambda)$ detector (for measuring illuminance), a standard white reference plate of known reflectance properties, and an alignment mirror. The optical axis is from the filament to the center of $V(\lambda)$ detector or of the white plate, whichever is in the alignment position. The filament should be oriented perpendicular to the optical axis so that the wires supporting the filament do not interfere with the distribution of its light. Alignment for the optical axis and reference plate must be accurate to 0.2° and be stable. The translation stage is used for changing the position of the detector, white plate, and mirror precisely. The responsivity of the $V(\lambda)$ detector must be sensitive and linear in the low-illuminance range. Set the LMD at 45° with respect to the standard white plate normal at an appropriate distance. The luminance factor $\beta_{0/45}$ of the standard white plate must be accurately known.



PROCEDURE: After the source has reached stabilization:

- 1. Move the translation stage and set the $V(\lambda)$ detector in the optical axis of the system.
- 2. Move the translation stage and set mirror in the optical axis of the system.
- 3. Set LMD in appropriate distance and aim the mirror center to make sure it is in 45° to the optical axis.
- 4. Move the translation stage and set standard white plate in the optical axis of the system.
- 5. Measure the luminance by LMD

ANALYSIS: The standard luminance is calculated by the following equation.

$$L = \frac{\beta \cdot E}{\pi}$$

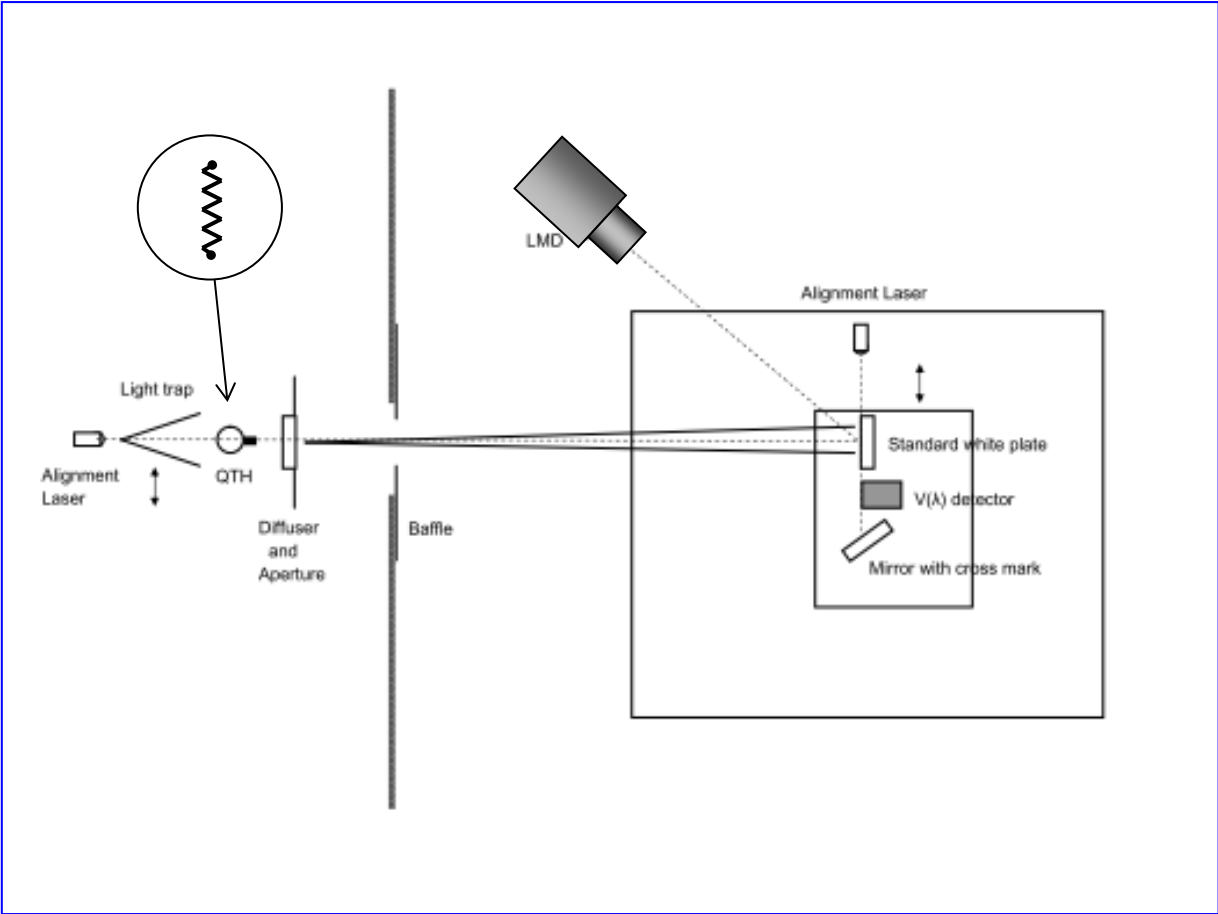
(1)

where L is luminance(cd/m^2) $\beta = \beta_{0/45}$ is the luminance factor of the standard white plate under source/detector (0/45) condition, E is the illuminance as measured by the $V(\lambda)$ detector.

REPORTING: Report the luminance measurement result and luminance of the white reference plate standard.

COMMENTS: The responsivity and linearity of $V(\lambda)$ detector should be previously calibrated with a standard procedure (e.g., CIE-69). The responsivity of the $V(\lambda)$ detector must be sensitive and linear in low illuminance range. The system should be in a quality darkroom. We diagram other possible methods below.

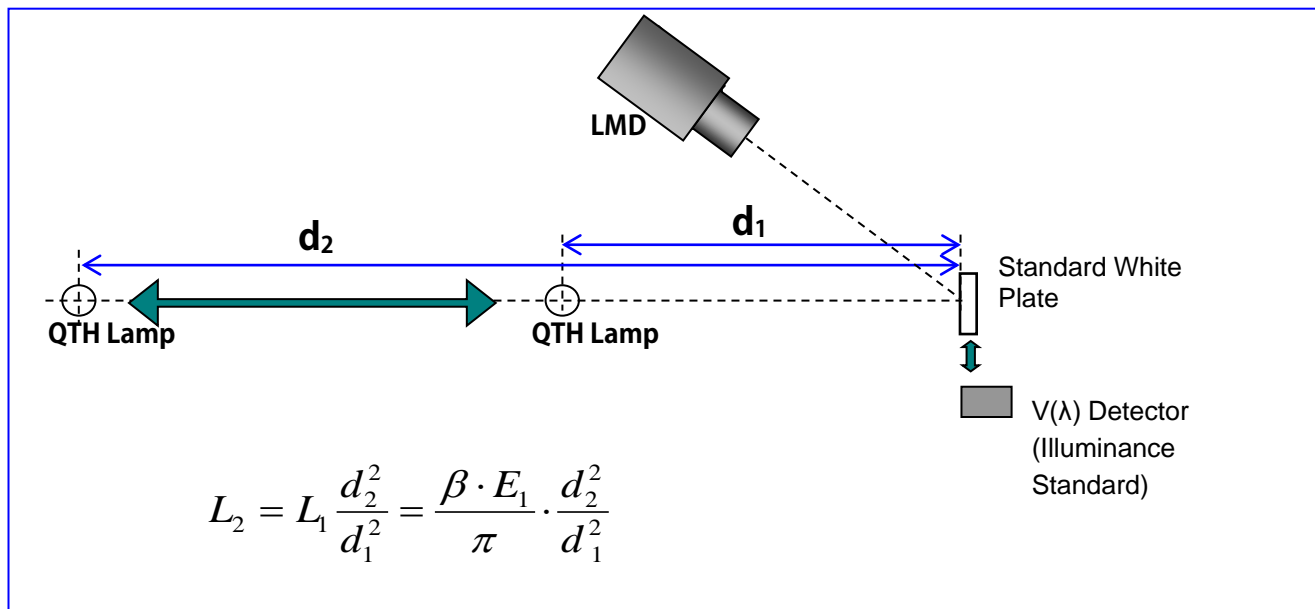
—SAMPLE DATA ONLY—		
Do not use any values shown to represent expected results of your measurements.		
Reporting example		
Standard (cd/m ²)	LMD(cd/m ²)	Error(cd/m ²)
0.030	0.029	0.001





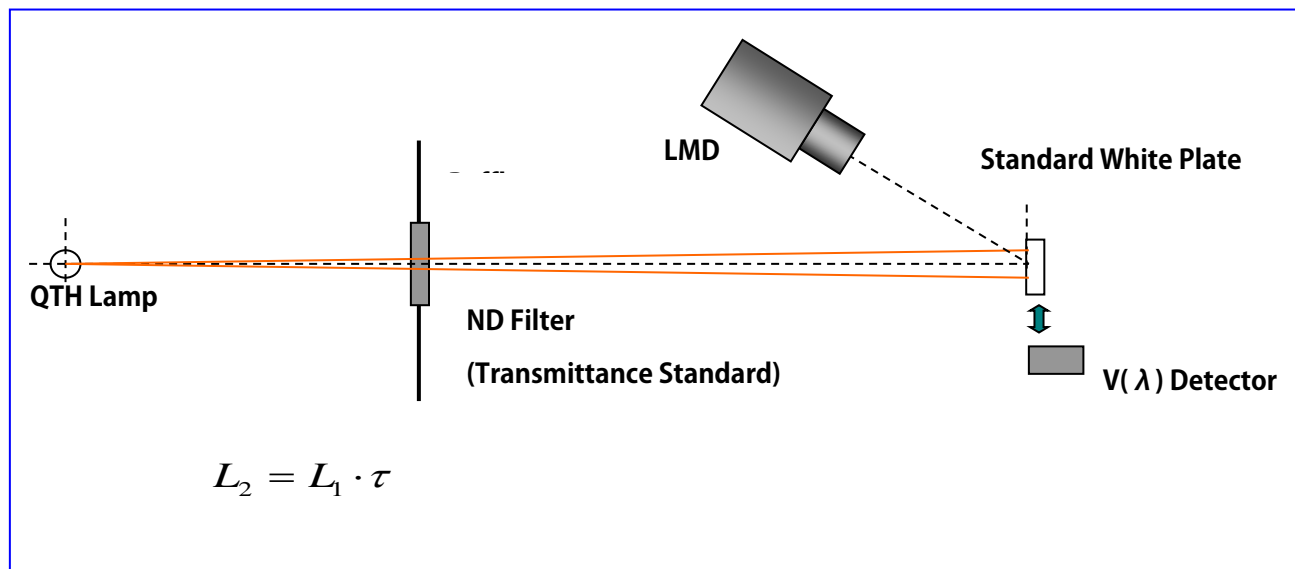
A3.2.1 STANDARD WHITE PLATE & CHANGE IN DISTANCE

E_1 is measured by standard $V(\lambda)$ detector in high luminance range at distance d_1 . L_2 is in low luminance range by moving the lamp farther to d_2 .



A3.2.2 STANDARD WHITE PLATE AND NEUTRAL-DENSITY (ND) FILTER

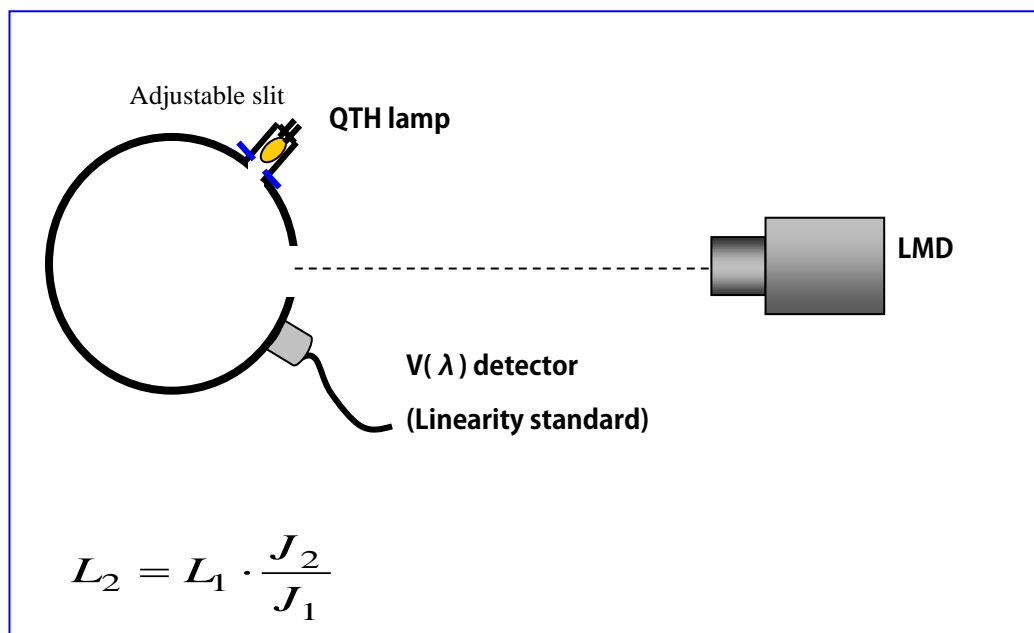
The ND filter transmittance τ must be accurately known. L_1 is measured by the luminance meter without the ND filter in place. L_2 is the low-luminance range with the ND filter in the middle between lamp and the standard white plate.





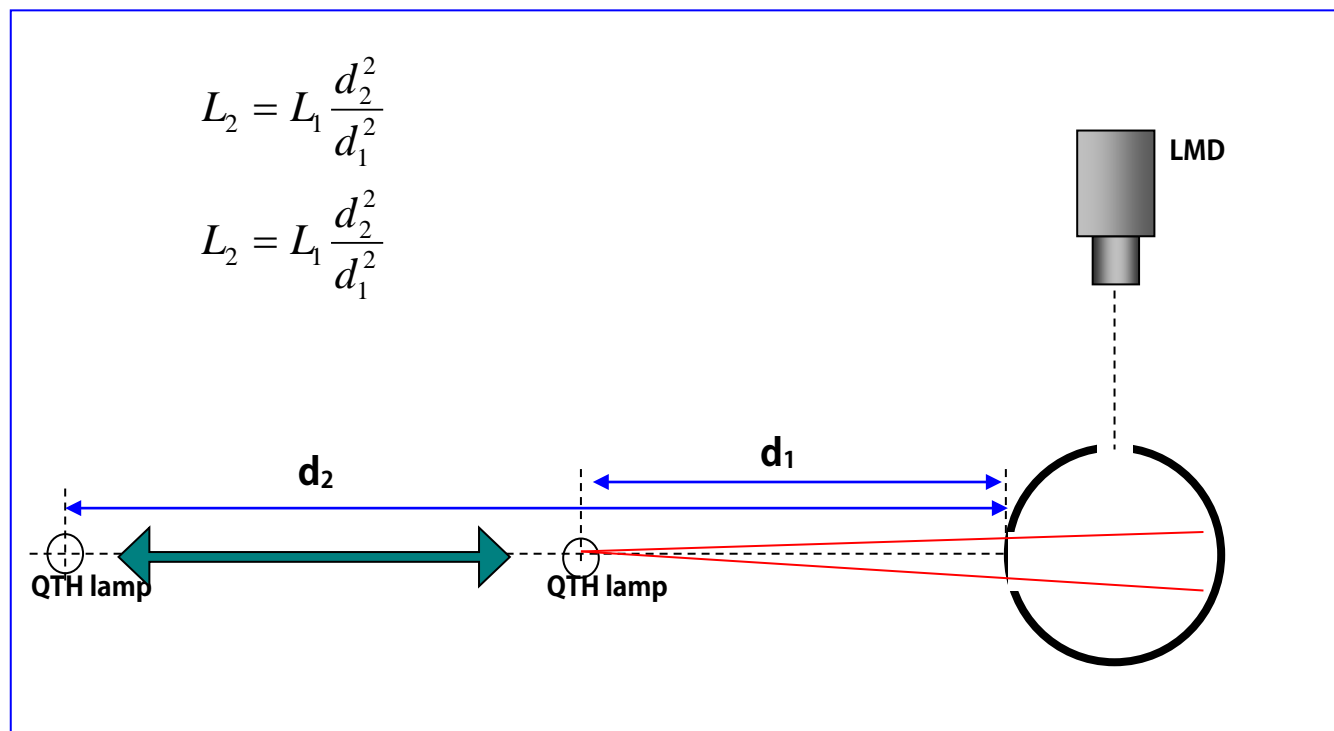
A3.2.3 INTEGRATING SPHERE WITH LINEAR DETECTOR

L_1 is a luminance is measured by a standard luminance meter and provides a calibration of the $V(\lambda)$ detector producing current J_1 . An adjustable slit or aperture on the source is closed producing a much lower luminance L_2 and associated current J_2 . The LMD luminance measurement result can then be compared with this low luminance L_2 . It is helpful if the slit or aperture does not appreciably change the spectral distribution of the source as their size changes.



A3.2.4 INTEGRATING SPHERE AND DISTANCE

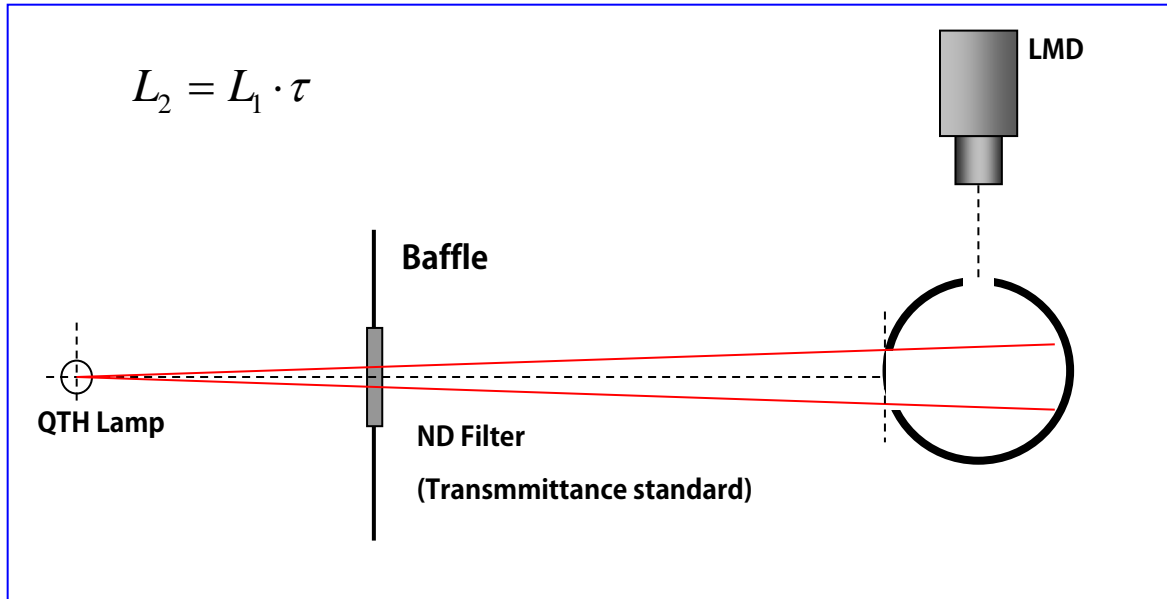
L_1 is a relatively large luminance as measured by a quality luminance meter. L_2 is a low luminance produced by moving the lamp farther away from the integrating sphere. Accurate measurements of the distances are critical. The initial distance d_1 should not be close to the sphere. Also, reflections must be carefully controlled and eliminated.





A3.2.5 INTEGRATING SPHERE AND ND FILTER

L_1 is measured by standard luminance meter without the ND filter. L_2 is a low luminance obtained by putting the ND filter in the middle between lamp and integrating sphere.



Low luminance measurement diagnostics of LMD

The accurate low luminance measurement is an important parameter in dark room contrast ratio, because a small measurement error in low luminance result induces drastic difference in contrast ratio. The light-measurement devices (LMD) involved in this section are subjected to test for its accuracy on low luminance measurement. The accuracy of a LMD on low luminance measurement is determined through measuring a standard low-luminance light source which can be achieved based on photometry standard and attenuation method as described below.

Photometry standard:

Photometry standards provide the luminance traceability to the primary standards of the National Metrology Institute for each country. Both source-based and detector-based methods are commonly used as transfer standards. Source-based methods employ a luminous-intensity standard lamp as a standard light source and rely on geometry conversions of inverse-square-law and luminance-illuminance relations for the reflectance on a white standard plate at the source/detector geometry of 0/45 (source at 0° [normal to the plane of the sample] and detector at 45° with respect to the normal of the sample). For the inverse-square-law, the relation between luminous intensity of the light source and illuminance on the reference plane is

$$E = \frac{I}{d^2} \quad (1)$$

where I is luminous intensity, E is illuminance, d is the distance from light source and reference plane. It is important to avoid any deviation from the necessary condition of inverse-square-law (CIE 69). As shown in Fig.1, $d \gg 2r$. If the condition is not fulfilled, then Eq (1) would be invalid. For example, the distance between the standard light-source and the reference plane should be kept at least ten times of the standard light-source size. When we set a standard white plate in the reference plane, the luminance-illuminance relation between the standard white plate and reference plane is defined as equation (2).

$$L = \frac{\beta}{\pi} E \quad (2)$$

where L is luminance and $\beta = \beta_{0/45}$ is luminance factor.



Detector-based method employs luminance meter or illuminance detector as a transfer standard. In the case of using luminance meter, an extended lower luminance range can be transferred from regular luminance range (above 1 cd/m^2) by making use of attenuation method. In the case of using Illuminance detector, standard luminance light source is realized by luminance-illuminance relation such as equation (2). Then extension of the luminance standard to low luminance level is obtained by attenuation method.

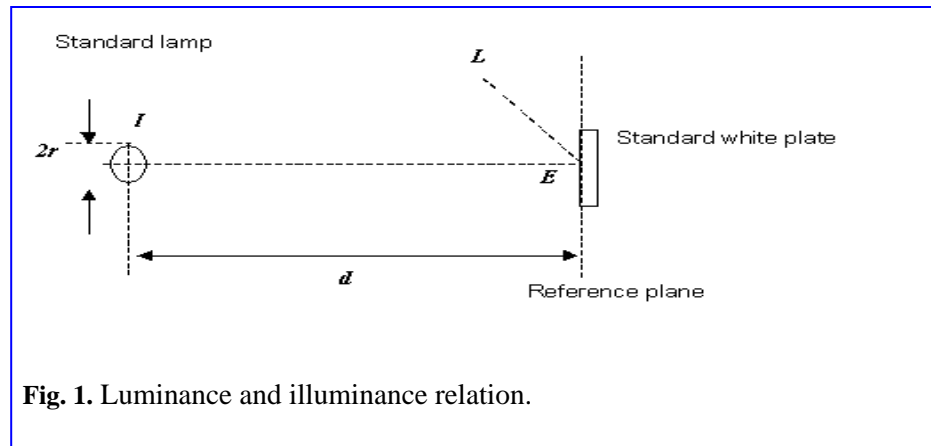


Fig. 1. Luminance and illuminance relation.

Attenuation method:

Attenuation method is to reduce the luminance level of the system to the low luminance level, which can be realized by integrating sphere, reflective diffuser, transmitting diffuser, variable aperture, neutral density filters (NDFs) or distance. It should be determined the reduction factor of the attenuation method that provides the standard traceability which makes the luminance extend to the low luminance level. The reduction factor could be obtained from detector linearity, precision distance or the transmittance of neutral density filters (NDFs). Detector linearity can be calibrated by beam addition method to determine the linear responsivity range for optical signal. The reduction factor of distance method is obtained by inverse-square-law. NDFs can be calibrated by transmittance system.

Example 1. White plate system:

In this system, photometry standard is realized by a $V(\lambda)$ detector which is calibrated for illuminance responsivity and linearity. Attenuation parts are a transmitting diffuser and distance. This system consists of a stable quartz tungsten-halogen lamp (QTH), a $V(\lambda)$ detector and a standard white plate in a low ambient light environment. The system is shown in Fig. 2. The light source is a stable low power QTH which power is 10 W. In appropriate distance (about 3.5 m), set a translation stage on which are set a $V(\lambda)$ detector, a standard white plate and an alignment mirror. The optic axis is from the filament center to the center of detector or white plate. Alignment for the optic axis and reference plane must be accurate enough. The translation stage is used to change the position of the detector, white plate and mirror precisely. The responsivity of the $V(\lambda)$ detector must be sensitive and linear in low illuminance range. Set LMD along the 45° to the standard white plate normal in appropriate distance.

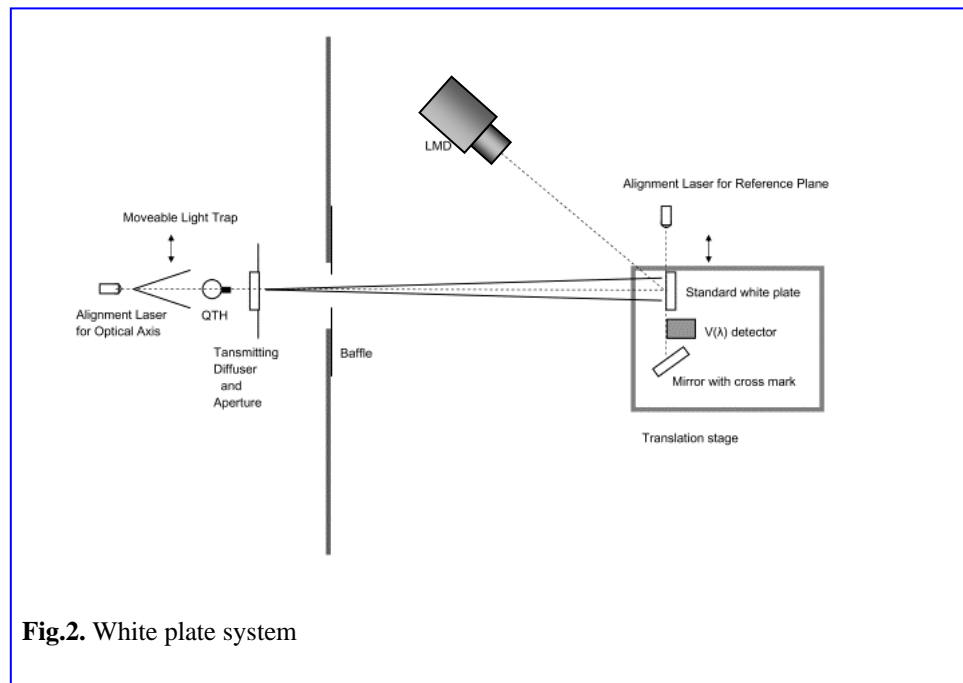


Fig. 2. White plate system

As an example, supposed the responsivity of the $V(\lambda)$ detector is 36.7 nA/lx and the linear range of output light current is from 0.2 nA to 0.1 mA. The 0/45 reflectance of the standard white plate is 1.014. It means that we can realize the illuminance level from 0.0054 lx to 2721 lx and the luminance level from 0.0018 cd/m^2 to 879 cd/m^2 by equation (2).



Example 2. Double integrating sphere system:

In this system, photometry standard is a standard luminance meter in regular luminance range. Reduction factor is obtained by a $V(\lambda)$ detector which is calibrated for linearity. Attenuation part is an integrating sphere. This system consists of a stable quartz tungsten-halogen lamp (QTH), a $V(\lambda)$ detector on first integrating sphere and a second integrating sphere. We can determine the linearity relation between output luminance of first integrating sphere output port and the detector signal by changing the variable aperture. Connect the second integrating sphere to the first integrating sphere and switch the variable aperture to maximum. Then measure the luminance of output port of second integrating sphere by luminance meter in regular luminance range and read the detector signal at the same time. The low luminance light source can be realized from luminance-signal ratio and linearity relation.

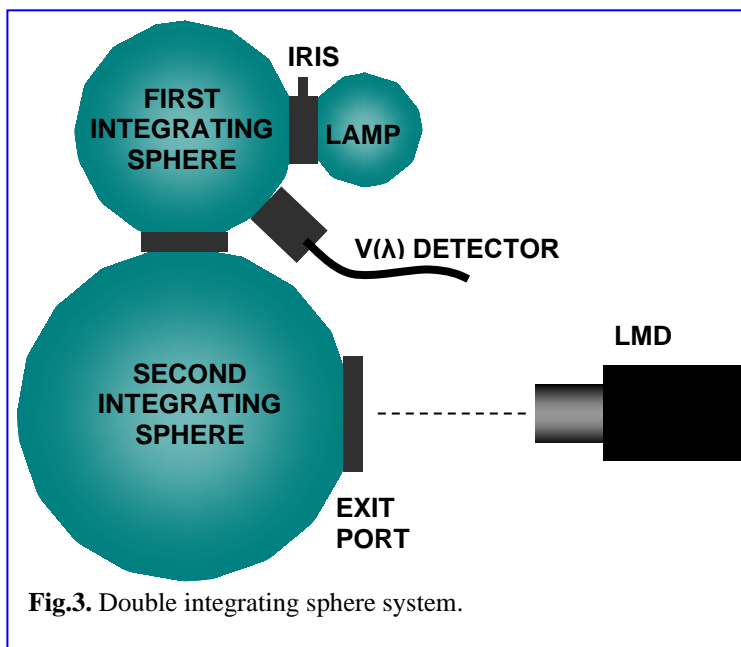


Fig.3. Double integrating sphere system.

A3.3 DETECTOR LINEARITY DIAGNOSTIC

The linearity of any light-measurement device (LMD) used in the procedures outlined in this document should be checked to assure accurate measurements. There are several methods that can be used to check the linearity of a LMD. Please also visit the previous Section A3 Low-Light Measurements for a detailed discussion of making accurate low-light measurements.

Integrating Sphere Variable Source with Photopic Detector: This is probably the best way to check linearity. Refer to Fig. 1. A small integrating sphere containing a tungsten-halogen lamp is mounted to a larger integrating sphere with a iris between the two spheres. This arrangement produces a uniform diffuse source that does not change its spectrum as the luminance is changed. For this diagnostic we don't need the neutral density filters (NDFs) to start with. If the photopic photodiode monitor is linear (for a simple photodiode bathed with this much light, this is generally a good assumption), then the luminance measured by the LMD L should track the photodiode output current J as the iris changes the luminance. If the ratio of the luminance to the photodiode current is not the same for all luminances (within the repeatability of the LMD), then the LMD may not be linear and made need correction, or the photodiode in the source may be changing its characteristics due to heating from the lamp, or the photodiode is improperly configured (improperly baffled so that it directly views the lamp exit port or the lamp source). That is, if the LMD is linear (and so it the photodiode) then

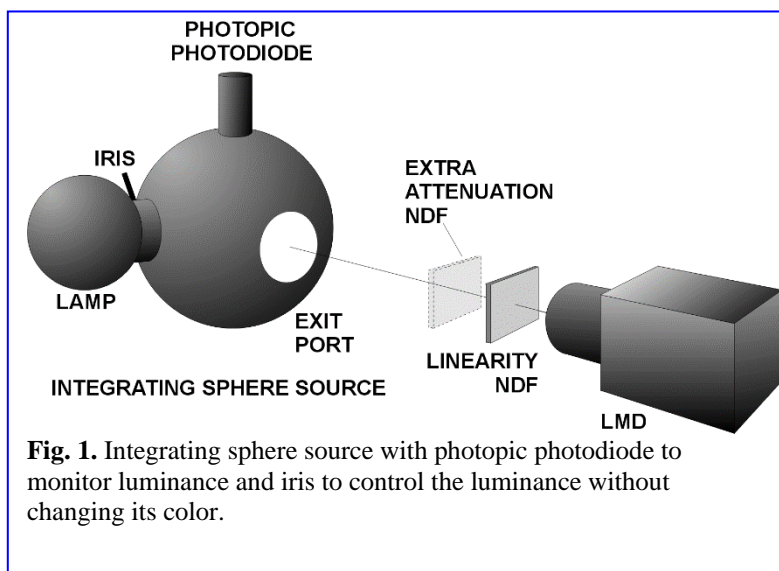


Fig. 1. Integrating sphere source with photopic photodiode to monitor luminance and iris to control the luminance without changing its color.

$$L = kJ, \quad (1)$$



where k is a constant ($\text{cd/m}^2/\text{A}$). For all the readings made see how much k changes over the range of luminance available. If you attempt to use a resistor in series with a photodiode and rely upon $V = IR$ to produce a voltage proportional to the current, be careful that R is not too large or the photodiode will not be able to supply enough power to drive the resistor appropriately, and the photodiode detector will appear nonlinear—this method is not recommended. It is much better to use a current amplifier or obtain an ammeter capable of accurate sub-microampere measurements.

If you want to check the low-level response of the LMD, then place an extra attenuation NDF in front of and near the lens of the LMD. If the LMD is linear, it should track the photodiode current so that $L = k'J$, where k' is a different constant. Note that as the luminance nears the lower end of the LMD's capability, rounding errors and digitization errors will eventually dominate. At such levels the LMD cannot be readily used.

When using the NDFs be careful of reflections from items in the lab illuminated by the light source reflecting off the NDF into the LMD. When using a NDF in this manner, it may be tempting to place it near and in front of the integrating sphere. This is not a good idea since anything in proximity to the exit port can dramatically change the luminance of the interior of the integrating sphere. It is best to place the NDFs as near to the LMD lens as is practical. If this is not done, then stray light reflecting off the lens can reflect off the NDF and back into the LMD.

Another way to check the system is by using an NDF taken in and out of the light path. Measure the luminance with L' and without L the linearity NDF near and in front of the lens of the LMD. Typically, we use an NDF with a density of 0.3 or 0.5. If the LMD is linear, then the ratio of L/L' should remain constant. This method can be carried to the low end of the LMD range by adding an extra attenuation NDF and checking that the ratio of the luminances with and without the linear LMD remains constant. This method doesn't rely on the photodiode, but the method will not catch slow deviations from linearity. In Fig. 2 we show the results of this NDF method of testing luminance linearity. Caution: many NDFs do not have a uniform attenuation over the entire visible spectrum, particularly this is true for NDFs made of gray glass. NDFs made from metal deposition on glass tend to have a more uniform attenuation over the visible spectrum.

There is another danger: If you attempt to use a light source that changes its luminance by changing the current in the lamp you will probably also be changing the spectral output of the lamp. This situation is undesirable as it introduces an uncontrolled variation into the experiment. A light source that changes its luminance without changing the spectral distribution of the light is preferred.

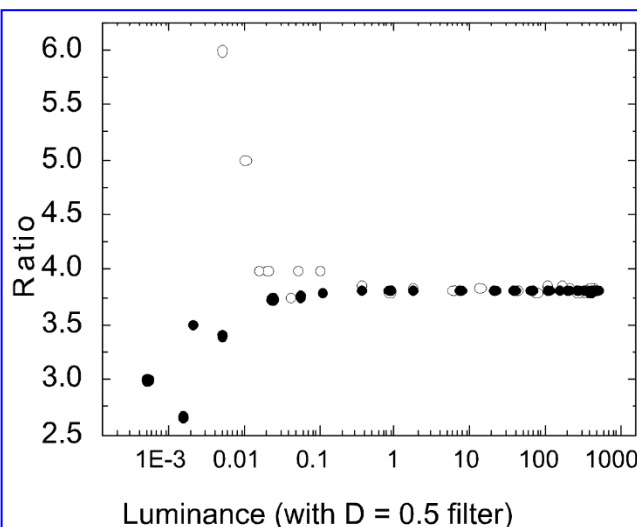


Fig. 2. Linearity test method measuring the ratio of the luminance without to the luminance with a neutral density filter having a density of 0.5 against the luminance measured in cd/m^2 . Two different luminance meters are compared. The large excursion comes from truncation errors associated with the number of significant figures in the readout.



A4 SPATIAL INVARIANCE AND INTEGRATION TIMES

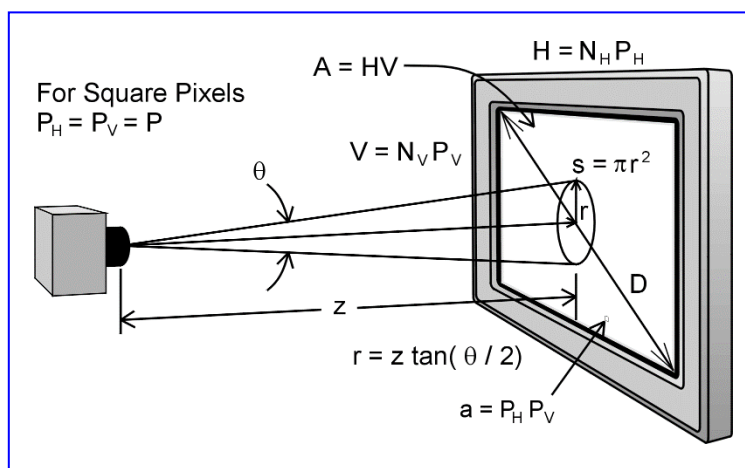
Abstract: Too short an integration time can alias with the screen refresh rate (if such exists). Also measuring too few pixels can result in a false representation of the true luminance of the display as well as changes in the luminance if the luminance meter moves slightly. Similar problems can arise with the measurement of colors.

There are two types of apertures associated with a luminance measurement, one is the aperture defined by the measurement field on the screen, the other is the "aperture" in time over which the measurement is made usually called the measurement time interval. Because the screen is composed of discrete pixels, moving the measurement field around on the screen can change the number of pixels contained in the aperture by a small amount especially if the measurement field is very small. If one were to move the LMD in one direction along the screen making measurements frequently, a beat-frequency pattern could emerge in the luminance-verses-position curve measured, i.e., an aliasing would occur owing to the well-defined measurement aperture and the discrete pixels. Similarly, because the screen can have a refresh rate associated with it whereby the pixels are turned off for a period of time, the finite measurement time interval can have an error in the number of screen refreshes it measures if it is not synchronized with the refresh period.

A4.1 NUMBER OF MEASURED PIXELS

How many pixels need to be measured for an accurate luminance measurement? That depends to some extent upon the pixel fill factor as well as the type of LMD used (how locally uniform the pixels are found to be). As the fill factor decreases below 100 %, the light measurement can change more as the LMD moves unless the LMD is covering a sufficient number of pixels, or some other factor mitigates the irregularities. In some cases, pixel-to-pixel irregularities in luminance (or color) can be large. (See § 3.2.8 Measurement Field, Angular Aperture, & Distance where this specification is introduced.) For simple LMD systems we suggest the following guidelines be used:

- 500 pixels or more is measured.
 - The measurement field of the LMD on the display surface ($2r$ in the figure) be less than 10 % of the horizontal and less than 10 % of the vertical dimension of the screen for the perpendicular orientation; that is, the measurement field ($s = \pi r^2$) will fit within a box on the screen having dimensions of $0.1 V \times 0.1 H$.
 - The LMD have a measurement field angle for infinity focus of 2° or less.
 - The lens of the LMD subtends 2° or less from the center of the screen—the measurement field angle should be 2° or less.
- If fewer than 500 pixels need to be measured, it is necessary to prove that such a measurement will not significantly contribute to the measurement error. Similarly, if any other of these conditions are not met, it must be proven that the measurement apparatus is able to provide a measurement that is equivalent to meeting these specifications. See the diagnostic below for a method to verify the adequacy of the number of pixels selected to be measured. There is no need to perform this diagnostic if more than 500 pixels are measured.



A4.1.1 DIAGNOSTIC—SUITABILITY OF CHOSEN NUMBER OF MEASURED PIXELS

Suppose you need to use fewer than 500 pixels and you want to test to see if it is reasonable to do this. Arrange for the LMD to measure the number of pixels you desire near the center of a full white screen. Stay within $0.1 V \times 0.1 H$ of the center of the screen. Find a visibly uniform field of pixels to measure in order to avoid anomalous pixels that will introduce errors. Be sure to rigidly mount both the LMD and the DUT so that they are securely in place and will not accidentally or inadvertently be moved. Note that this kind of verification or diagnostic need only be made on one type or class of a display-LMD combination when a series of displays are measured. It does not need to be performed on all displays. In other words, it is sufficient to measure less than 500 pixels if it is possible to prove that a class of apparatus can adequately meet these criteria for a certain class of displays.

1. Take a series of measurements on the properly warmed-up DUT and establish the **repeatability of the measurement** of the luminance (or color) with the DUT and the LMD held fixed. Determine the average value μ and its standard deviation σ using at least $n = 10$ measurements. (See § 5.2 Measurement Repeatability for more information and a



procedure if needed.) It would be expected that σ would be smaller than the measurement repeatability requirement of this document ($\sigma_{\text{LMD}} = 0.5\%$) and would certainly expect that it would be less than twice the measurement repeatability requirement, that is, $\sigma \leq 2\sigma_{\text{LMD}} = 1\%$ —this assumes your LMD has a smaller repeatability than the requirement of this document. If this is not the case and a repeated measurement of ten values doesn't improve the situation, then it may be indicative of a problem with the LMD, the display (perhaps not warmed up or unstable), or the combination of the two (see the next section A4.2.1 for temporal modulation of the luminance).

2. Make multiple measurements of the luminance (or color) as you transversely move the LMD relative to the screen a distance of $y = 5$ px vertically and then $x = 5$ px horizontally (or vice versa) making measurements at the spacing of five increments per pixel, $\Delta x = P_H/5$, $\Delta y = P_V/5$, for a total of 50 measurements. (It is easiest to do this with the LMD or display on a positioning system.)
3. Determine the mean μ' and standard deviation σ' of the 50 measurements. Also calculate the maximum deviation Δ_{max} between the lowest and highest measured value of the 50 measurements.
4. Criterion of acceptability: If the standard deviation of the 50 measurements is twice the LMD repeatability requirement or less ($\sigma \leq 2\sigma_{\text{LMD}} = 1\%$) and if the maximum deviation is less than six times the LMD repeatability requirement ($\Delta_{\text{max}} \leq 6\sigma_{\text{LMD}} = 3\%$), then it is permissible to use the number of pixels selected to make the measurements.

A4.1.2 CALCULATION EXAMPLES: NUMBER OF PIXELS MEASURED & DISTANCE

Standard 500 mm Distance Examples: In the following examples we provide a variety of equations that will permit the calculation of the number of pixels measured assuming a round measurement aperture. We also show some sample calculations. Finally, there is a table showing some common display configurations and the number of pixels measured for a 2° or 1° measurement field angle at a distance of $z = 500$ mm from the display. We discuss other measurement distances below the table that follows.

Example 1. Given an LMD with an measurement field angle (MFA) subtending $\theta = 1^\circ$ (radian measure of $2\pi\theta/360^\circ$) at a distance of $z = 500$ mm from the screen which has a pixel pitch in both horizontal and vertical directions of $P_H = P_V = 0.333$ mm so that the area allocated to each pixel is $a = P_H P_V = 0.111$ (mm)², then the radius of the circle being measured on the screen is $r = z \tan(\theta/2) = 4.36$ mm, the area measured on the screen (measurement field) is $s = \pi r^2 = 59.8$ (mm)², and the number of pixels measured within the LMD aperture on the average is $N = s/a = 549$ px. Putting this all together, the number of pixels measured is given by

FOR SQUARE PIXELS

$$N = \frac{s}{a} = N_T \frac{s}{A} = \frac{\pi r^2}{HV} N_T = \frac{\pi r^2}{P^2}, \text{ or}$$

$$N = \pi \left[\frac{z \tan(\theta/2)}{D} \right]^2 (N_H^2 + N_V^2), \text{ or}$$

$$N \cong \frac{\pi}{4} d^2 \frac{(N_H^2 + N_V^2)}{D^2},$$

(where in the last equation it is assumed that $z \gg r$)

A = area of the screen (viewable area, of course)
 $N_{H,V}$ = number of pixels, horizontal, vertical
 P_H, P_V = pixel pitch in the horizontal/vertical direction
 P = pixel pitch for square pixels
 H = horizontal size of screen = $N_H P_H = N_H P$ (for square pixels)
 V = vertical size of screen = $N_V P_V = N_V P$ (for square pixels)
 r = radius of round measurement area on screen
 s = area of screen being measured = πr^2 (Goal : $s < A/100$)
 $d = 2r$ = diameter of round measurement area on screen
 (should be less than 10% of H and V)
 a = area allocated to one pixel = $P_H P_V$ (= P^2 for square pixels)
 N_T = total number of pixels on the screen = $N_H N_V$
 N = number of pixels being measured on the screen (Goal : 500 px)
 z = distance from the screen to the LMD
 $D = \text{diagonal} = \sqrt{H^2 + V^2} = P \sqrt{N_H^2 + N_V^2}$
 Note that D is the exact diagonal of the viewable display surface.
 θ = LMD angular field of view ($^\circ$ or rad : $^\circ = \text{rad} \cdot 360^\circ/2\pi$)
 (NOTE : for small angles $< 10^\circ$, $\sin \theta \cong \tan \theta \cong \theta$ within 1%,
 where $\theta \cong d/z$ must be in radians)

Example 2. Following Ex. 1, if the round angular measurement field angle measures 2° , the area measured at a distance of 500 mm is 239 (mm)² (radius of 8.73 mm), and with a pitch of 0.333 mm; then the number of pixels would be



2000. With the 2° aperture at a distance of 500 mm the maximum square pixel pitch which will yield 500 pixels being measured is $P = 0.692$ mm ($P^2 = s/N$).

Example 3. Suppose we know the pixel pitch for horizontal $P_H = 0.723$ mm and vertical $P_V = 0.692$ mm, and the measurement field angle of the LMD $\theta = 1^\circ$. How far away z would the LMD need to be in order to capture $N = 500$ px? Using the formula in Ex. 1, we solve for z :

$$z = \sqrt{\frac{NP_H P_V}{\pi \tan^2(\theta/2)}}, \quad \text{where} \quad \begin{cases} N = \text{number of pixels measured on screen} \\ z = \text{distance from screen to LMD} \\ P_{H,V} = \text{pixel pitch, horizontal, vertical} \\ \theta = \text{LMD angular field of view } (^\circ, \text{ or rad : } ^\circ = \text{rad} \cdot 360^\circ/2\pi) \end{cases}$$

This gives a distance of $z = 1445$ mm.

Example 4. If we only have the diagonal measure $D = 14.2$ in (361 mm), the number of pixels in the horizontal $N_H = 640$ and vertical direction $N_V = 480$, and we know that the pixels are square; then we can determine the number of pixels measured by a LMD with angular measurement field angle of $\theta = 1^\circ$ and distance from the screen of $z = 500$ mm:

FOR SQUARE PIXELS

$$N = \frac{s}{a} = N_T \frac{s}{A} = \frac{\pi r^2}{HV} N_T = \frac{\pi r^2}{P^2}, \quad \text{or}$$

$$N = \pi \left[\frac{z \tan(\theta/2)}{D} \right]^2 (N_H^2 + N_V^2)$$

$$\begin{cases} N = \text{number of pixels measured on screen} \\ s = \text{area of screen measured} = \pi r^2 \\ a = \text{area allocated to one pixel} = P_H P_V = P^2 \quad (\text{for square pixels}) \\ N_T = \text{total number of pixels on screen} = N_H N_V \\ A = \text{number of pixels measured on screen} \\ H = \text{horizontal size} = N_H P_H = N_H P \quad (\text{for square pixels}) \\ V = \text{vertical size} = N_V P_V = N_V P \quad (\text{for square pixels}) \\ z = \text{distance from screen to LMD} \\ N_{H,V} = \text{number of pixels, horizontal, vertical} \\ D = \text{diagonal} = \sqrt{H^2 + V^2} = P \sqrt{N_H^2 + N_V^2} \\ \theta = \text{LMD angular field of view } (^\circ \text{ or rad : } ^\circ = \text{rad} \cdot 360^\circ/2\pi) \end{cases}$$

For the values here, $N = 294$, which is an insufficient number according to our suggestion of 500 pixels (the LMD-display combination would have to be verified for adequacy)—see § 3.2.8 Measurement Field, Angular Aperture, & Distance for initial comments about the 500-pixel suggestion. If the pixels are not square, we would need to know the exact aspect ratio $\alpha = H/V = N_H P_H / N_V P_V$ in order to calculate the pixel pitch and determine the area of a pixel. In such an unlikely event, the general formula is

$$N = \pi \left[\frac{z \tan(\theta/2)}{D} \right]^2 (1 + \alpha^2) / \alpha, \quad \text{where} \quad \begin{cases} \alpha = \text{aspect ratio} \\ N = \text{number of pixels measured on screen} \\ z = \text{distance from screen to LMD} \\ N_{H,V} = \text{number of pixels, horizontal, vertical} \\ D = \text{diagonal (of entire screen matrix)} \\ \theta = \text{LMD measurement field angle } (^\circ \text{ or rad : } ^\circ = \text{rad} \cdot 360^\circ/2\pi), \end{cases}$$

which reduces to the above formula when the pixels are square ($\alpha = N_H/N_V$).

**Table 1.** Number of Pixels Measured and Percent of Screen Diagonal Measured for Several ConfigurationsDec.=decimal, No.=number of, z = distance between DUT and LMD, θ = MFA, α = aspect ratio, D = diagonalThe shaded area denotes failure to comply with 500-pixel and ≤ 10 %-of-diagonal convention.

Display Pixels		Diagonal		z	θ	Aspect Ratio α		Size of Screen				Measurement Region			No. pixels
N_H	N_V	(in)	(mm)	(mm)	(°)	Dec.	Ratio	H (in)	V (in)	H (mm)	V (mm)	$d = 2r$ (mm)	in % of D	% Area	N
640	480	10.4	264	500	2	1.333	4:3	8.32	6.24	211	158	17.46	6.6%	0.71%	2195
640	480	21.0	533	500	2	1.333	4:3	16.80	12.60	427	320	17.46	3.3%	0.18%	538
640	480	21.0	533	500	1	1.333	4:3	16.80	12.60	427	320	8.73	1.6%	0.04%	135
640	480	21.0	533	500	2	1.333	4:3	16.80	12.60	427	320	17.46	3.3%	0.18%	538
640	480	5.2	132	500	2	1.333	4:3	4.16	3.12	106	79	17.46	13.2%	2.86%	8779
640	480	5.2	132	500	1	1.333	4:3	4.16	3.12	106	79	8.73	6.6%	0.71%	2194
640	480	32.0	813	500	2	1.333	4:3	25.60	19.20	650	488	17.46	2.1%	0.08%	232
800	600	11.3	287	500	2	1.333	4:3	9.04	6.78	230	172	17.46	6.1%	0.61%	2905
800	600	15.0	381	500	2	1.333	4:3	12.00	9.00	305	229	17.46	4.6%	0.34%	1648
800	600	22.6	574	500	2	1.333	4:3	18.08	13.56	459	344	17.46	3.0%	0.15%	726
1024	768	12.1	307	500	2	1.333	4:3	9.68	7.26	246	184	17.46	5.7%	0.53%	4151
1024	768	15.0	381	500	2	1.333	4:3	12.00	9.00	305	229	17.46	4.6%	0.34%	2701
1024	768	6.4	163	500	2	1.333	4:3	5.12	3.84	130	98	17.46	10.7%	1.89%	14836
1024	768	6.4	163	500	1	1.333	4:3	5.12	3.84	130	98	8.73	5.4%	0.47%	3709
1024	768	21.0	533	500	2	1.333	4:3	16.80	12.60	427	320	17.46	3.3%	0.18%	1378
1280	1024	13.0	330	500	2	1.250	5:4	10.15	8.12	258	206	17.46	5.3%	0.45%	5897
1280	1024	25.0	635	500	2	1.250	5:4	19.52	15.62	496	397	17.46	2.7%	0.12%	1595
1280	1024	17.0	432	500	2	1.250	5:4	13.27	10.62	337	270	17.46	4.0%	0.26%	3449
1280	1024	42.0	1067	500	2	1.250	5:4	32.80	26.24	833	666	17.46	1.6%	0.04%	565
1280	1024	23.0	584	500	1	1.250	5:4	17.96	14.37	456	365	8.73	1.5%	0.04%	471
1280	1024	23.0	584	500	2	1.250	5:4	17.96	14.37	456	365	17.46	3.0%	0.14%	1884
1280	1024	60.0	1524	500	2	1.250	5:4	46.85	37.48	1190	952	17.46	1.1%	0.02%	277
1920	1080	17.0	432	500	2	1.778	16:9	14.82	8.33	376	212	17.46	4.0%	0.30%	6228
1920	1080	42.0	1067	500	2	1.778	16:9	36.61	20.59	930	523	17.46	1.6%	0.05%	1020
1920	1080	12.0	305	500	2	1.778	16:9	10.46	5.88	266	149	17.46	5.7%	0.60%	12500
3072	2240	13.5	343	500	2	1.371	11:8	10.91	7.95	277	202	17.46	5.1%	0.43%	29418

Other Measurement Distances: Whereas the typical standard measurement distance in this document is 500 mm and is based upon the use of computer monitors, there are other measurement distances that will be used depending upon the display size, use, and purpose. Some LMDs cannot focus closer than 1 m and other instruments must be used at a distance of only a few millimeters as with conoscopic LMDs; such LMDs can be used provided their results will agree with LMDs used at the standard measurement distance of 500 mm. Many hand-held displays should be measured at a distance of from 250 mm to 400 mm. Many television displays will be measured at greater distances as will front-projection displays. Thus, there can be no set distance required for all displays.

The suggested method of choosing a proper measurement distance that is independent of the type of display is based on a limit of average human visual acuity R , which we will take as $R_{48} = 48$ pixels/degree of visual angle,¹ or for excellent vision of bright targets we can use $R_{60} = 60$ px/degree.² To convert this resolution limit to a distance D , we need to know the size P of the pixel in mm/px, where we will assume square pixels, and the angle viewed in degrees, θ .

$$D = R\theta P / \tan(\theta).$$

¹ For 48 px/degree see Olzak, L. A., & Thomas, J. P. (1986). Seeing spatial patterns. In K. R. Boff, L. Kaufman & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 1, pp. 7.1-7.56). New York: Wiley.

² For 60 px/degree with very bright targets see, e.g., *The Encyclopaedia of Medical Imaging*, H. Pettersson, Ed., p. 199. Taylor & Francis, UK, 1998.



Setting $\theta = 1^\circ$ gives:

$$D_{48} = (48 \text{ px})P/\tan(1^\circ) = (2750 \text{ px}) P, \text{ for } R_{48} = 48 \text{ pixels/degree},$$

and

$$D_{60} = (60 \text{ px})P/\tan(1^\circ) = (3437 \text{ px}) P, \text{ for } R_{60} = 60 \text{ px/degree}.$$

As an example, a full HD display has a resolution of 1920x1080 pixels. Applying the 2750 pixel distance would indicate a measurement distance that is 2.54 times the screen height V , $D = (2750/1080) V$, which is a typical working distance for a television. If we use $R_{60} = 60 \text{ px/degree}$, we obtain $D = 3.18V$, or 3.2 screen heights). For entertainment television the 2750 px P (or 2750 P with pixels in mm and not mm/px) distance is optimal for viewing. Then you will be readily seeing all the pixels you are paying for. For computer monitors a 500 mm distance will often be less than the 2750 P distance because you may normally want to see better than the pixel resolution for ease of reading fine text.

A4.2 MEASUREMENT TIME INTERVAL

(Integration time required)

The integration time of the LMD must not be so short that the refresh rate of the screen will affect the luminance measurement more than is allowed by the required measurement uncertainty and precision of the LMD. Some LMDs can be synchronized with the refresh rate of the screen (if applicable), but even so, the measurement time interval can play a role in the uncertainty of the measurement.

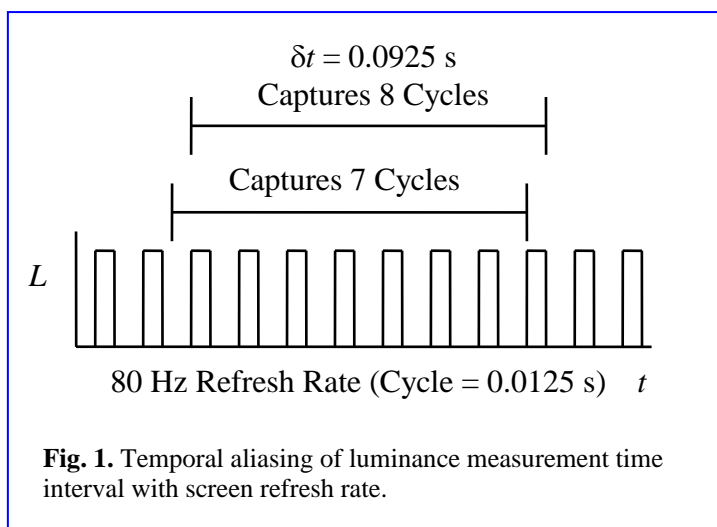
A4.2.1 TEMPORAL MODULATION OF LUMINANCE

Some LMDs integrate the light over a time interval (or several time intervals) and report the measurement to the user. Some displays have a refresh rate associated with them where the luminance is pulsating in time but fast enough so that it is not objectionable to the eye (otherwise flicker is noted) or there may be a modulation of the luminance from an ac-powered backlight. When the integration time is short compared to a number of cycles of its modulation (< 200 or so) the measured luminance can change significantly depending upon when the measurement time interval occurs and how many pulses or cycles are measured. For example, in the figure we show a refresh rate of $R = 80 \text{ Hz}$ with the measurement time interval as $\delta t = 0.0925 \text{ s}$, then on the average there will be 7.4 refresh cycles captured by the instrument [No. cycles = $R \delta t = \delta t/(1/R)$]. But for any single measurement the number of refresh cycles captured can be from 7 to 8 which would give a range of luminance errors from -5.4 % to +8.1 %.

A4.2.2 DIAGNOSTIC—VERIFICATION OF ADEQUATE INTEGRATION TIME

The adequacy of the integration time interval can be checked after the display is warmed up. The measurement time interval for a white screen must be long enough so that the standard deviation σ of ten or more luminance measurements (taken quickly) is no greater than twice the measurement repeatability σ_{LMD} allowed for the luminance meter in this document or 1 % ($\sigma \leq 1 \%$, $\sigma_{\text{LMD}} = 0.5 \%$); see § 5.2 Measurement Repeatability if more details are needed on how to do this properly. If the standard deviation is too large, one explanation for this is that the integration time is too short. The problem can be solved either by using a neutral density filter, by taking the average of a number of measurements, or by synchronizing the LMD with the light pulses from the display (an available feature with some LMDs).

Extension of Integration Time: The measurement time interval can be extended using a calibrated neutral density filter (NDF), and the standard deviation of the luminance measurement re-measured. Given that the density of the filter is D , then the transmission T of the filter is $1/10^D$ and the integration time is extended by a factor of $1/T = 10^D$; for typical densities: $D = 0.3$, $1/T = 2.00$; $D = 0.5$, $1/T = 3.16$; $D = 1.0$, $1/T = 10$, etc. If after the extension of the integration time the standard deviation does not appropriately decrease, then other instability problems may exist in the LMD, the display, or both. Be careful in using NDFs. Some have transmissions that are wavelength dependent and may not be suitable for use with photopic or color measurements. The NDFs made from metallic deposition on glass tend to be much less





wavelength dependent while the gray-glass type can exhibit a wavelength dependence that can corrupt a luminance measurement beyond what is tolerable in this document.

Averaging Several Measurements: How many measurements are required to be comfortable that the mean of a series of n measurements reflect the true value of the measurand, e.g., luminance? Assuming that the distribution of the measurements about the true value of the measurand is represented by a normal (or Gaussian) distribution, the standard deviation of the mean is given by $\sigma_N = \sigma / \sqrt{n}$. Make enough measurements n so that σ_N is no greater than twice the repeatability of the LMD as above ($\sigma_N \leq 1\%$, with $\sigma_{LMD} = 0.5\%$).

A5 ADEQUACY OF SINGLE MEASUREMENTS

Making Single Measurements: Generally speaking, the measurement repeatability of any LMD will be much smaller than its uncertainty of measurement. At the time of this writing, the best luminance calibration and measurement is usually $\pm 0.5\%$ with a coverage factor of $k=2$, but that is at the national standards laboratory level—not a typical luminance meter. The measurement repeatability of any LMD can be 1/10 of its accuracy of measurement or smaller.

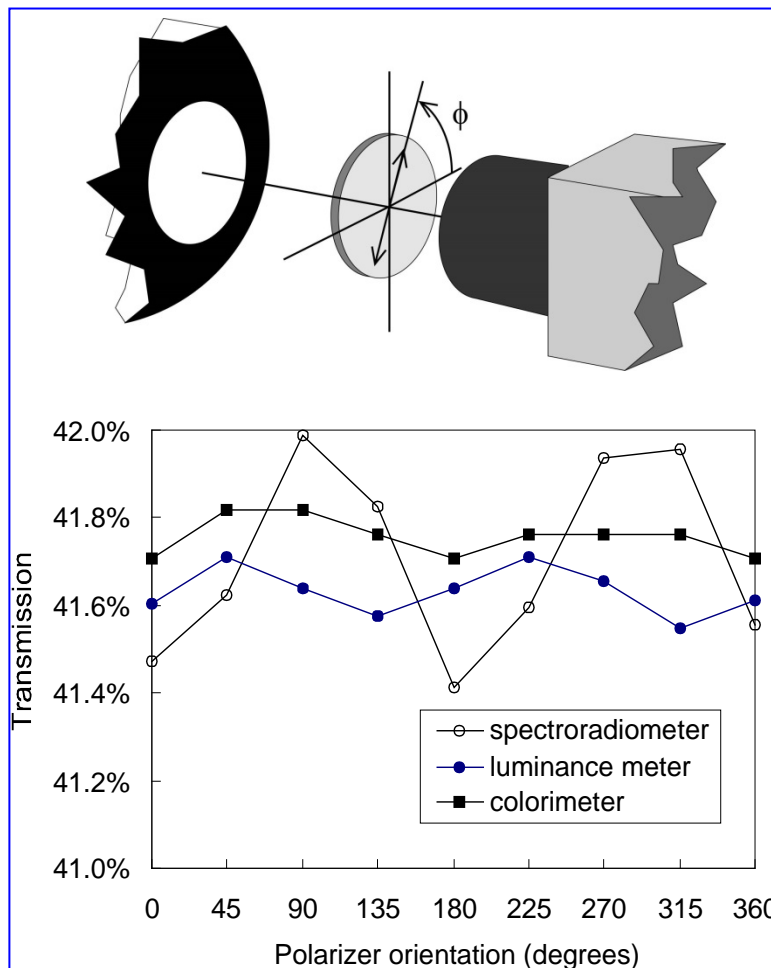
The issue of how many measurements need to be made to establish any measurement result was discussed—in part—in the introductory comments for the appendix § B1 Radiometry, Photometry and Colorimetry. In this document, we call for making only one measurement for each quantity to be measured. Often people feel the need to make multiple measurements of each quantity where the mean and standard deviations are reported. That, of course, is permissible throughout this document. There are several reasons for our only requiring a single measurement. Photometry and colorimetry are sciences for which the short-term imprecision of the measurement usually is much smaller than the inaccuracies as noted above. This has to do with the determination of the candela from fundamental standards. Once it has been determined that the measurement time interval is not too small so that the luminance measurement is not affected by any refresh rate associated with the display (see A4 Spatial Invariance and Integration Times), there is little value obtained in making multiple measurements—except to check results. As far as comparing the results of one laboratory with another, the $\pm 2\%$ or $\pm 4\%$ uncertainty of measurement and methods used are the problem, not the repeatability (shot-to-shot imprecision) of the measuring instrumentation. For the sake of simplicity and speed, we have opted not to require tedious multiple measurements until the fundamental quantities are substantially more accurately determined. In all our measurements, there is no objection to making multiple measurements and reporting the average values. It is always suggested that multiple measurements be made in order to uncover any possible problems, but we don't require them because a number of those using this document will be making many measurements on many displays and will have a keen sense of how well their instrumentation is working. Thus, you can make single measurements, but you have to know the repeatability of the results—see § 5.2 Measurement Repeatability to measure the standard deviation, the repeatability, using a coverage factor of two, would be twice the standard deviation. The results have to reproduce within the repeatability of the LMD, then the instability of the DUT is negligible, and you can trust the single measurement. If the variation of multiple readings is much larger than the repeatability of the LMD, then there may be instabilities of the DUT, the LMD, or other unknown uncertainties in the measurement. If the single-measurement criteria (of multiple measurements being within the repeatability of the LMD) is not obtained, then the true repeatability (twice the standard deviation) must enter in the final uncertainty determination of the measurement—see A10 Uncertainty Evaluations.

If there are no substantial aperture or time-interval effects introducing errors in the measurement (see above section A4), then making a number of measurements, taking the average and standard deviation, will reflect little more than the measurement repeatability of the instrument. It is probably a good idea, from time to time, to make a number of measurements of a white screen holding the LMD in a fixed position to assure yourself of a small measurement repeatability and that there are not unanticipated problems. However, there is little value in insisting on making multiple measurements for each luminance value desired, until the uncertainty of measurement of the LMD is comparable to its imprecision. If there is any question how to make mean and standard deviation measurements, see § 5.2 Measurement Repeatability for guidance.



A6 POLARIZATION EFFECTS DIAGNOSTICS

There are two main sources of polarized light in emissive displays: the backlight of an LCD display is polarized during transmission and reflected light off the surface of the display can be polarized. To determine any sensitivities of the LMD to this polarized light, the following procedure is recommended. Simply place a polarizer between the LMD and a stable uniform light source (such as an integrating sphere source or equivalent) and measure the luminance of the source for different angles of rotation of the polarizer. The figure shows a typical measurement setup and resultant data. Note that the polarizer should be close to the LMD and far away from the integrating sphere so that it doesn't affect the output of the integrating sphere. A simple sheet polarizer film or glass polarizing filters can be used and placed in a graduated rotational mount. At minimum, two points should be measured: the orientation that provides the maximum transmission and the orientation that provides the minimum. If the source is not polarized and the detector is insensitive to polarization, then the ratio of the luminance of the source without the polarizer to the luminance with the polarizer should be constant for any angle of rotation. For a good polarizer, this ratio should be around 40 % to 45 %. The figure also shows an example of the plot L_ϕ/L_0 versus ϕ , where ϕ is the angle of rotation of the polarizer, L_ϕ is the measured source luminance with the polarizer rotated by ϕ degrees, and L_0 is the initial measured source luminance (with no polarizer). This figure shows examples only of older instruments; such results should not be expected. As instrumentation is improved their sensitivity to polarization is usually reduced as well. More recent spectroradiometers will probably show much less polarization sensitivity.





A7 COLOR MEASUREMENT DIAGNOSTICS

Suppose you purchase an array spectroradiometer or a tristimulus colorimeter and a calibrated tungsten-halogen light source. You measure the source with your LMD, and you get the proper luminance L_w as well as the proper chromaticity coordinates x_w, y_w (or whatever color space you need to use). Yet when you look at the chromaticity diagram you realize that this is just one point in the gamut. Is there any way to be reasonably sure that the LMD will measure the other colors correctly without having a number of radiometrically calibrated lamps or filters? (Even if you don't have a calibrated standard light source, the failure of the LMD to perform these measurements may indicate a problem with the instrument.) If pure monochromatic light, such as from a laser, is measured, the chromaticity coordinates obtained from the instrument should fall very near or on the spectrum locus of a standard color space. Similarly, if a narrow-band interference filter is measured, then the measured chromaticity coordinate should also be close to the spectrum locus.

The distance from the measured chromaticity coordinates to the spectrum locus depends upon the bandwidth of the illumination, and the errors of the measuring instrument (see Fig. 1). Interference filters can provide an inexpensive and straightforward method to confirm the performance of spectroradiometers and colorimeters in measuring highly saturated colors. If the instrument can accurately measure several points along the spectrum locus (especially near 400 nm and 700 nm), and a known white point (such as from a calibrated source), and if the instrument is linear, then the operator should feel comfortable with the ability of the instrument to measure any point (color) within the spectrum locus.

A spectroradiometer or colorimeter with imaging optics views the central part of the interference filter. An aperture is provided to ensure that the edge of the filter is not used in the measurement (this outer diameter region is where the filter can be non-uniform). A light-transmitting diffuser made of opal glass is used to provide uniform illumination. An optional neutral density filter can be used to attenuate the light if it is too bright or to test the uniformity of the results with a change in light intensity. The light source can be an incandescent lamp or an integrating sphere source.

A simplified geometry of the apparatus is shown in Fig. 2. There are at least three sources of errors associated with the measurement configuration: the characteristics of the interference filter (bandwidth, temperature coefficient, drift), the dispersion introduced by light which is not parallel to the normal of the interference filter, and an overall error in establishing the normal direction of the interference filter. These errors would cause the data to shift from the calculated values, although if care is taken, the dispersion and alignment errors can be made negligible. Any background light or scattering within the instrument could be an additional factor. Finally, how the instrument handles any background subtraction may also be a factor revealed with the use of interference filters. Using a spectroradiometer, a substantial signal for frequencies far removed from the interference filter peak can indicate undesirable scattering within the instrument. A He-Ne laser (e.g., $\lambda = 632.8$ nm) is also a good way to check for unwanted scattering.

The most rigorous way to evaluate the measured results would be to have the interference filters calibrated for spectral transmittance immediately before measurements are made and compared with the calculated chromaticity coordinates. When this method is not available, data provided by the filter manufacturer can be used. When the manufacturer's data are used, one should consider that the filter characteristics are subject to long-term drift and temperature dependency.

In a typical configuration we arrange the elements as shown in Fig. 2. We set the distance between the LMD and the interference filter to be from 50 cm to 1 m, depending upon the instrument. A filter holder is chosen to ensure that each filter used is placed in the same position. We use the reflection of the lens of the LMD in the interference filter to align the optics.

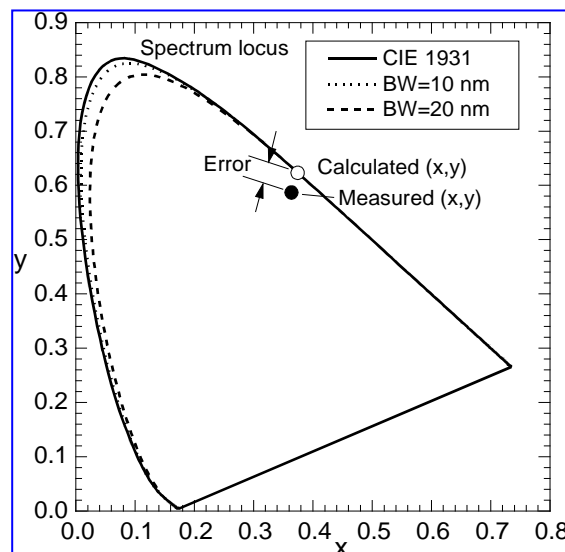


Fig.1.Spectrum Locus

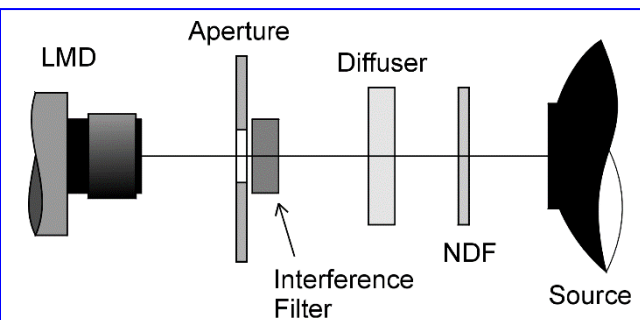


Fig. 2. Apparatus. Separations of filters and diffuser from the source are exaggerated for illustration purposes. Since the absolute luminance level is not important, the filters may be placed close to the exit port to minimize the generation of stray light.



Once this alignment is made, the holder is not repositioned. We eliminate background illumination as much as possible by shrouding the apparatus with black felt to avoid any stray light. Be careful that the interference filter is not heated by environment. It is best to put the highly reflective side of the interference filter facing the source to minimize any heating. The diffuser is not necessary if an integrating sphere is employed.

Procedure: The luminance and chromaticity coordinates should be recorded for a selection of interference filters (with bandwidth less than 10 nm) and plot the data on the chromaticity diagram to see how close they come to the spectrum locus. In the case of the spectroradiometers, the dominant wavelength, spectral purity, radiometric transmittance, and spectral response can also be recorded. Enough readings should be taken for each filter to obtain some understanding of how well the LMD deals with saturated colors. The greatest difficulty in reaching the Locus will likely be found nearest the ends of the visible spectrum (400 nm and 700 nm).

SOURCES OF ERROR:

As stated earlier, if the LMD is properly calibrated for obtaining the correct color of a standard white point (e.g., CIE illuminant A), and if the measured colors of the interference filters fall on or near the spectrum locus, then all other colors within the color gamut should be measured accurately by the device. If the interference-filter data points shift away from the locus more than their bandwidth would permit, then make sure care has been taken with the alignment of the apparatus, and good interference filters chosen. Also, check for stray light contributions to the measurement. Look for any stray light (not the light from the interference filter) illuminating the front of the LMD that would appear in a reflection off the interference filter. The bandwidth of the filters can account for some displacement from the locus toward the center of the color gamut (see Fig. 1, bandwidth especially affects the displacement in the green region). If all these sources of error are accounted, then the location of the measured data point with respect to the spectrum locus can provide some information on the behavior of the instrument.

Figure 3 shows a small segment of the spectrum locus (around 530 nm) and some data points. If the measured data does not fall on the ideal point on the locus, its position in reference to the "true" point can indicate possible sources of error. Shifts along the spectrum locus could result from calibration errors or indicate a mismatch of filters in tristimulus colorimeters. Shifts toward the white point would indicate internal scattering of light within the measuring device, possibly stray-light leakage (including infrared), and inadequate subtraction of a background signal. Detector noise could cause the data to fall on either side of the locus. Some devices subtract a no-light background from the light measurement and can lead to negative readings owing to noise. If any negative data is truncated, the resulting chromaticity-coordinate data points could shift slightly inward. Thus, if good filters are used and care is taken with the setup, the placement of the data in relation to the locus can indicate how the instrument performs with respect to its specifications and your own expectations.

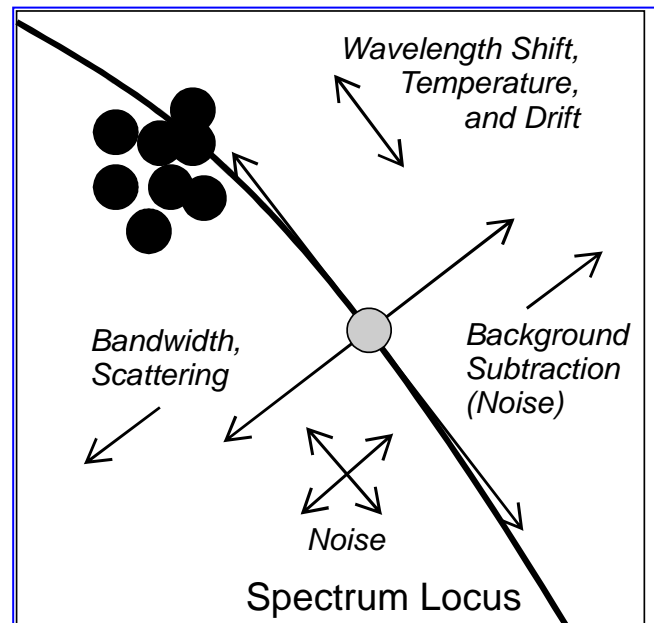


Fig. 3. Sources of error that can move a data point away from its ideal position on the spectrum locus.

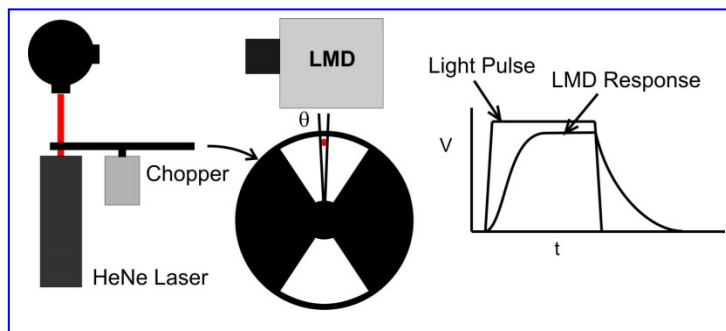


A8 TEMPORAL RESPONSE DIAGNOSTICS

The temporal response of any light-measurement device (LMD) used in the procedures outlined in this document may be checked to assure accurate measurements. The methods described in this section are effective for checking the temporal response of devices such as photodiodes and photomultiplier tubes whose output can be measured directly. The temporal response of a LMD is determined by measuring the response of a LMD to a light pulse. Light pulses of a known duration and rise time can be formed using a He-Ne laser and a light chopper or a pulse generator and an LED.

CHOPPER AND LASER:

The light beam from the laser passes through the chopper and into the entrance port of an integrating sphere whose exit port faces the LMD under test. (This need not be a laboratory grade integrating sphere. Almost any enclosure with a white interior having two appropriate ports will do.) The reason for using an integrating sphere is to prevent damage to your LMD by directing the laser beam directly into the LMD. The period of the light pulse must be of sufficient duration to measure the response of the LMD. The best that can be done for equal on and off

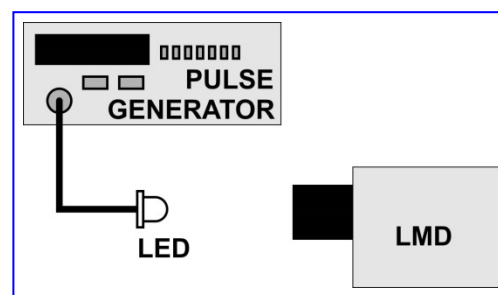


times of the pulse is by using two openings (to balance the chopper) with an arc length of 90° . To ensure that you are measuring the response time of your LMD the light pulse is required to have a rise time much less than the response time of the LMD under test. To achieve a light pulse with a minimum rise time the light chopper should be positioned where the laser beam has the smallest cross section, i.e., as close as possible to the output laser. Otherwise, divergence in the beam will cause the beam to spread giving the light pulse a longer rise time. Also, the beam should be close to the rim (outer diameter) of the chopper; the higher the angular velocity of the opening the shorter the rise time of the pulse.

As an example, suppose the laser beam has a diameter of $d = 1$ mm and passes through the chopper at a distance of $x = 20$ mm from the axis of the wheel. The rotation angle associated with this width of the laser beam would be $\theta = d/x = 1\text{mm}/20\text{mm} = 0.05$ radians. If we assume we have a chopper with a rotation rate of $R = 10$ rps (revolutions per second: $60\text{ rpm} = 1\text{ rps}$, where rpm = revolutions per minute) then the angular velocity would be $\omega = 2\pi R = 63$ radians/sec. Therefore, the rise time of the light pulse would be $\theta/\omega = 790\text{ }\mu\text{s}$; at $R = 100$ rps (6000 rpm) the rise time of the light pulse would be $79\text{ }\mu\text{s}$.

LED AND PULSE GENERATOR:

Another way to test the temporal response of the LMD is to power a fast LED with a good pulse or square-wave generator. This is especially important for testing response times in the sub microsecond and nanosecond regimes. Fast LEDs are readily available (response times in the nanoseconds). They can be tested using a fast photodiode or fast PMT (photomultiplier tube). Watch out for proper termination of the cable connecting the LED to the generator (or proper output impedance of the generator) so that reflections in the cable don't interfere with the measurement—this is especially important if you are worried about sub microsecond measurements. (Some display technologies require a sub microsecond response times, so such reflections can pose a problem.) For sub microsecond pulses, substantial voltages ($> 10\text{V}$) may be required to make the LED light pulse sufficiently bright to be seen or measured.





A9 ARRAY-DETECTOR MEASUREMENTS

In addition to the general requirements already outlined in A1, there are complications in using array detectors such as CCDs and digital cameras. There are several sources of error associated with array detectors. Here we are talking about the entire imaging system including the lens, we are not limiting all our remarks to the array element by itself. You can have an array detector element that is perfect with exactly the same response for each array pixel. But when it is put into a system with a lens, the entire imaging system likely no longer preserves that uniformity because of the performance of the lens, reflections, etc. Thus, there are several factors to consider when using an array photodetector:

1. **Nonuniform response over array.** This is the nonuniform responsivity from pixel to pixel in the photodetector array including any nonlinearity and differing linearities in response for pixels or columns of pixels. There can be defective detector pixels and small regions where the response is different than the average response. Many of these problems can be accounted for via a flat-field correction (5).
2. **Nonuniform imaging from lens system.** The properties of the lens used which contributes to nonuniformity such as vignette (the $1/\cos^4$ fall off, see B>>>) and shutter vignette. Shutter vignette can be observable when a mechanical shutter is used with the array detector and not all parts of the array receive the same exposure—this can be a problem especially for short exposures. There are other problems encountered with lens systems, such as the change in image luminance with focus.
3. **Glare, veiling glare, lens flare.** The lens system and the components associated with it often produce a stray light that provides a nonuniform background illumination that depends upon the scene being viewed as well as the lens configuration (e.g., different f-stops).
4. **Background subtraction.** Appropriate background signal needs to be subtracted from any acquired signal. If the array is not thermally regulated, backgrounds need to be measured often.
5. **Flat-field corrections.** Appropriate correction needs to be made for the nonuniformity of system response whenever the most accurate measurements are required. The flat-field correction provides a detector pixel-by-pixel adjustment so that all the detector pixels have the same response to the same amount of light. It is usually an array of numbers that multiplies the measurement array after background subtraction to adjust for nonuniformities of the entire system. The problem here is creating the appropriate arrangement to provide a uniform source from which a uniformity calibration can be made.
6. **Photopic response.** For luminance measurements a photopic filter is required. This assumes that each detector pixel has the same spectral responsivity (this may not always be the case).
7. **Aliasing between the detector pixel and the display pixel.** When the spatial frequency of the image of the display pixel is anywhere near the spatial frequency of the detector pixel, you can get aliasing and a resulting modulated picture. Defocusing the lens or putting a diffusion filter (from a camera store, for example, or glass plate with some hair spray on it) in front of the lens may help, but this may not be a reproducible way to regulate the light.
8. **Calibration in luminance.** If the array detector, such as a CCD, provides you with counts and you need luminance values instead; then the array detector must be calibrated. Measure the same uniform source with the array LMD and a luminance meter—the exit port of an integrating sphere works well or use a white diffuse standard. Let L be the luminance measured by the luminance meter and S be the value obtained from the array LMD. The correction factor is $c = L/S$, and future measurements by the array detector can be converted to luminance by multiplying the array LMD values by c .

When we speak of linearity, we mean the output from each detector pixel S_i is related to the luminous flux hitting the detector pixel by $S_i = m_i\Phi + b_i$ where m_i is independent of flux Φ for all the detector pixels. The background subtraction removes b_i , and the flat-field correction k_i produces the same response for each pixel, or $k_i m_i = m = \text{constant}$. To achieve a uniform response the response of the detector pixel S'_i is corrected according to $S'_i = (S_i - b_i)k_i = m\Phi$, for all array detector pixels. As long as m_i is not a function of Φ this will be a successful operation. Of course, the background and the signal are both noisy, so this will never work perfectly.

Given that each detector pixel can be corrected to assure uniformity for any particular system and object (the DUT) configuration, lens flare or veiling glare is still a particular concern. In general, the amount of glare depends upon the lens used and the configuration of the detector, but it also depends upon the size and position of the light sources being measured. You can get a different glare simply by moving the object (the DUT) closer so that the object being measured (the DUT) subtends a larger solid angle. What this means is that the flat-field correction with one configuration may not be adequate for another configuration. Changing the f-stop of the lens (aperture), the position of the light source (the DUT), the pattern of light on the screen, etc., all affect the glare contribution to the array. Hopefully, you will be fortunate so that all these problems represent only a few percent error in measured light.

How can we tell if we have a problem? Ideally if we had a uniform light source that was an exact replica of the light we were trying to measure, we could make a good flat-field correction (FFC). For example, suppose you wanted to measure the uniformity of the entire surface of a DUT with a CCD camera, and suppose the CCD is perfect and linear. If we setup the DUT, determined the position and size of the white full screen to be measured, then removed the DUT and replaced it with a



uniform light source that had the same shape as the white screen and was placed at the exact same position, then we could produce a flat-field correction that accounts for the imperfections of the system for that particular configuration. Such a light source is generally not available.

If you are fortunate enough to have a lens with very little veiling glare, you may be able to create one FFC and use it with many configurations. Here is an example of a procedure to test how well one FFC will work. It assumes adequate image processing software is available to manipulate the images as desired. Using a quality integrating sphere with an exit port luminance nonuniformity of 1 % or less. Place it a distance away from the array detector system so that the image of the exit port is slightly larger than the array when the exit port is in sharp focus (you will have to move the integrating sphere off axis a little to focus on the exit port)—the goal is to fill the image of the exit port with the array as much as possible. Adjust the light source so that you are getting readings well above the background but not saturating the detector array. For example, if the maximum counts attainable per CCD detector pixel is 16,384 before saturation, a luminance that produces 10,000 counts or so would be reasonable.

Take a background image $B(x,y)$ with the lens cap on the lens (or equivalent). (It may not be sufficient to simply take a background with the shutter closed if the shutter-closed background is different from the background taken with the lens cap on the lens, it is best to use the background with the lens cap.) Then obtain a raw image of the exit port $R(x,y)$ and subtract off the background image to obtain the net image $N(x,y)$. Obtain the average of the net image for all pixels:

$$\mu = \frac{1}{n} \sum_{\text{image}} N(x, y),$$

where there are n total detector pixels. The FFC is given by $F(x,y) = N(x,y)/\mu$, and will be approximately equal to one for all FFC pixels. Now, all future images can be corrected $C(x,y)$ using the background and FFC by

$$C(x, y) = [R(x, y) - B(x, y)] / F(x, y).$$

To see how well this FFC works for other situations, change the position of the integrating sphere; move it nearer to the lens and further away obtaining a series of raw images for each position. Be sure the focus is always made on the exit port of the integrating sphere. Include one image of the exit port far enough away that it fills less than half the array. You can also change f-stops if that is possible on your system. Obtain the corrected images for all the different positions of the integrating sphere $C_i(x,y)$ and examine how uniform the exit port is found to be in all the images. Any nonuniformity you observe in the exit port images is an indication of the upper bound of the usefulness of your FFC. If in the distant image you find the exit port shows a 5 % nonuniformity, or the near focus image shows a nonuniformity of 10 %, then you cannot use that FFC for all measurements from which you expect accuracy. Further, you will have to take a FFC for each configuration you want to use. It would be difficult to create a uniform luminance surface the size of the display at the same position that the display is to be measured. Hopefully, you will find the FFC to be able to provide you with a less than 2 % nonuniformity for the display images that are approximately the same size as the image used to create the FFC.

If it is unknown and unknowable, then
why do we want to know it??



Hint B21.



A10 UNCERTAINTY EVALUATIONS

We present a summary of error propagation and then apply it to several specific measurements in this document. For more detail, see the many books that cover this subject. For a discussion of the proper terminology to use with statements of errors see the appendix B21 Statements of Uncertainty.

In general, every quantity Q we attempt to measure is a function of other variables or parameters in the experiment so we can write $Q = Q(p_1, p_2, p_3, \dots, p_n)$. Each parameter p_i has an uncertainty Δp_i associated with it. If we want to ask how Q is affected by small changes in the parameters p_i , we could set up an experiment where we change each parameter by its estimated uncertainty (in either the positive or negative direction) and re-measure Q for each change. The change in Q can be expressed in terms of its partial derivatives:

$$\Delta Q = \sum_{i=1}^n \frac{\partial Q}{\partial p_i} \Delta p_i, \quad (1)$$

where the Δp_i are the changes in the parameters and ΔQ is the resultant change in Q . To take an average of a number N of the ΔQ should result in zero since the changes can be negative or positive, in general. A better measure of the error would be the square-root of the average of the squares of the ΔQ . So, for $k = 1, 2, \dots, N$ such experiments we have as the average uncertainty in ΔQ expressed as

$$(\Delta Q)^2 = \frac{1}{N} \sum_{k=1}^N \left(\sum_{i=1}^n \frac{\partial Q}{\partial p_i} \Delta p_i \right)_k^2 = \frac{1}{N} \sum_{k=1}^N \left(\sum_{i=1}^n \left(\frac{\partial Q}{\partial p_i} \Delta p_i \right)_k^2 \right) + \frac{1}{N} \sum_{k=1}^N \left(\sum_{i \neq j} \frac{\partial Q}{\partial p_i} \frac{\partial Q}{\partial p_j} \Delta p_i \Delta p_j \right)_k. \quad (2)$$

If the parameters are independent: Over a large number of such experiments, the second term on the right—the cross-terms—will eventually average to zero since both positive and negative changes in the parameters are allowed, and because the parameters' uncertainties are independent of one another. An estimate of the anticipated change in Q will result when the parameters are all changed by their anticipated uncertainties. Since the changes in the parameters are squared in the first term their respective signs are not important; dropping the cross-terms, Eq. 2 reduces to

$$(\Delta Q)^2 = \sum_{i=1}^n \left(\frac{\partial Q}{\partial p_i} \Delta p_i \right)^2. \quad (3)$$

Another useful expression is the relative uncertainty where we divide Eq. 3 by Q^2 to obtain

$$\left(\frac{\Delta Q}{Q} \right)^2 = \sum_{i=1}^n \left(\frac{1}{Q} \frac{\partial Q}{\partial p_i} \Delta p_i \right)^2. \quad (4)$$

This often results in an algebraic simplification of the uncertainty expression. The uncertainty ΔQ or relative uncertainty $\Delta Q/Q$ is the square-root of the sum on the right side of the equation.

Equation 3 is a statement of the propagation of errors from the independent parameters that contribute to the resulting measurement. If any one of the parameters p were dependent upon other variables r_j , then a similar expression would be used to estimate the anticipated error in Δp in terms of the uncertainties Δr_j and the partial derivatives $\partial p / \partial r_j$ just as expressed in Eq. 3. Then that Δp value would be used in the expression for ΔQ —a compounding of errors, a propagation of errors. There are certain circumstances when Eq. 3 becomes rather simple. Suppose Q depends upon a multiplication of the

powers (positive or negative) of the parameters, such as $Q = \prod_{i=1}^n p_i^{s_i}$ where the s_i are positive or negative real numbers, for

example $Q = A^n B^m C^r D^s$. If we calculate ΔQ by Eq. 3 and divide by Q^2 we obtain the relative uncertainty of Q that has a particularly simple form:

$$\text{for } Q = \prod_{i=1}^n p_i^{s_i} \text{ then } \left(\frac{\Delta Q}{Q} \right)^2 = \sum_{i=1}^n \left(s_i \frac{\Delta p_i}{p_i} \right)^2 \quad (5)$$

$$\text{e.g., for } Q = A^n B^m C^r D^s \text{ then } \left(\frac{\Delta Q}{Q} \right)^2 = \left(n \frac{\Delta A}{A} \right)^2 + \left(m \frac{\Delta B}{B} \right)^2 + \left(r \frac{\Delta C}{C} \right)^2 + \left(s \frac{\Delta D}{D} \right)^2. \quad (6)$$

Here, the s_i as well as n, m, r, s , can be any positive or negative real number.

Another case of interest is the situation where Q is a sum of other quantities: $Q = p_1 + p_2 + p_3 \dots + p_n$. Equation 3 is, of course, still valid. When we have such a sum, we often have that the p_i are similar in size, $p_i = p$, and all have approximately the same uncertainty Δp each. Should this be the case, then some simplification occurs:



$$(\Delta Q)^2 = \sum_{i=1}^n (\Delta p_i)^2 \cong n \Delta p^2, \quad \text{and with } Q \cong np \text{ we can estimate } \left(\frac{\Delta Q}{Q} \right)^2 \cong \frac{1}{n} \left(\frac{\Delta p}{p} \right)^2, \text{ or } \left| \frac{\Delta Q}{Q} \right| \cong \frac{1}{\sqrt{n}} \left| \frac{\Delta p}{p} \right|. \quad (7)$$

Thus, the relative uncertainty in such a sum decreases inversely as the square-root of the number of terms in the sum.

When we purchase a measurement instrument, such as a luminance meter, the manufacturer will provide a statement of uncertainty U_m that is usually an expanded uncertainty with a coverage factor of $k = 2$ —you must always check this with the manufacturer. The associated combined standard uncertainty is $u_m = U_m/2$ is likely a root-sum-of-squares of the calibration uncertainty of their transfer standard (traceable to the appropriate national metrology institute) u_c , the repeatability of the measurement of that standard s_m , and various other factors such as drift, temperature effects, focus, distance, etc. With luminance meters, since the repeatability is often much smaller than the uncertainty, the manufacturer may quote the repeatability of that instrument s_m to give you an idea of how well the instrument can make relative measurements in a short time period. Such an uncertainty statement and its related repeatability is often made in connection with a particular, CIE Illuminant A, for example. How well the instrument does for other colors and sources may not be stated. Further, the stated uncertainty may only apply to luminances above a certain threshold. Thus, without clear specifications from the manufacturer, it may not be appropriate to apply the stated uncertainty of a luminance meter to low-light level readings.

A10.1 LUMINANCE MEASUREMENT UNCERTAINTIES

The manufacturer tells us that his instrument has a relative uncertainty of $U_m/L = 4\%$ and a relative repeatability of $s_m/L = 0.2\%$. We will assume that this U_m is an expanded uncertainty with a coverage factor of $k = 2$. When we make a single measurement, the uncertainty of our measurement result would be U_m , that is, we will assume the repeatability has already be folded into the uncertainty. If we were to make several measurements of an absolutely stable light source in a short period of time, we would expect that the standard deviation of that set of results would be approximately the repeatability s_m .

Suppose we make several measurements of the luminance L_i , $i = 1, 2, 3, \dots, n$ and determine the mean L_{ave} and standard deviation s_L of the resulting set; but we find that the standard deviation is significantly larger than the repeatability of the instrument, $s_L > s_m$. What do we then use for the uncertainty? Obviously, there is some instability somewhere. If we cannot improve the apparatus to eliminate the increased uncertainty, then we must incorporate it into the uncertainty estimate that we would provide to characterize our measurement capability. The combined standard uncertainty is the root-sum-of-squares of the component uncertainties (see appendix B21 Statements of Uncertainty). Assuming the uncertainty of the LMD includes a $k = 2$ coverage factor, we wouldn't use U_m as a component of uncertainty, but we would have to eliminate the coverage factor thereby using $U_m/k = U_m/2 \equiv u_m$ as the component of uncertainty that is associated with the instrument. The combined standard uncertainty for our luminance measurement would be

$$u_L = \sqrt{\left(\frac{U_m}{k} \right)^2 + s_L^2} = \sqrt{\frac{U_m^2}{4} + s_L^2}. \quad (8)$$

Finally, we reintroduce a $k = 2$ coverage factor to obtain $U_L = 2u_L$, which is properly called the *expanded uncertainty with a coverage factor of $k = 2$* . It is U_L that we would use in quoting the final uncertainty of our luminance measurement.

Example: With our above example of $U_m = 4\%$ we will assume that the manufacturer used a $k = 2$ coverage factor in establishing the measurement uncertainty of the LMD. Further, let's assume that the relative standard deviation of the set of measurements with respect to the average L_{ave} is $s_L/L_{ave} = 1.2\%$. Using Eq. 8, we would obtain $u_L/L_{ave} = 2.3\%$, and the relative expanded uncertainty with a coverage factor of $k = 2$ would be $U_L/L_{ave} = 4.6\%$.

A10.2 CHROMATICITY COORDINATES MEASUREMENT UNCERTAINTY

We have a similar situation as in the above luminance measurement, except that the repeatability of the chromaticity measurement is not necessarily much smaller than the uncertainty of measurement of the instrument. For a single measurement, we would be inclined to accept the manufacturer's uncertainty statement of U_m . Thus, when we make single measurements, we must be aware of the possibility of an increased uncertainty from random effects (type A—see B21) than we may find with the luminance measurement.

Let c be any one of the chromaticity coordinates. Suppose the uncertainty of measurement of the instrument is $U_m = 0.0024$ and the repeatability is $s_m = 0.0005$. Also, suppose we take a series of measurements of the chromaticity coordinates of some source and find that the standard deviation $s_c = 0.0015$ of those measurements. Since the standard deviation of the set is in excess of the repeatability, then we will want to account for it as another component of uncertainty. Assuming that the manufacturer uncertainty estimate U_m is an expanded uncertainty with a coverage factor of $k = 2$, then the combined standard uncertainty of any chromaticity measurement would be



$$u_c = \sqrt{\left(\frac{U_m}{k}\right)^2 + s_c^2} = \sqrt{\frac{U_m^2}{4} + s_c^2}, \quad (9)$$

or $u_c = 0.0014$. We would quote an expanded uncertainty of $U_c = 2u_c = 0.0028$ with a coverage factor of $k = 2$.

A10.3 CONTRAST MEASUREMENT UNCERTAINTIES

When Two Luminance Meters Are Used: The error in the contrast $C = L_w/L_b$ is based on a luminance measurement of white L_w and black L_b . If a different luminance meter is used to measure white than is used to measure black, then the relative uncertainty in the contrast measurement is, from Eq. (6),

$$\left(\frac{u_c}{C}\right)^2 = \left(\frac{dC}{C}\right)^2 = \left(\frac{dL_w}{L_w}\right)^2 + \left(\frac{dL_b}{L_b}\right)^2 = \left(\frac{u_w}{L_w}\right)^2 + \left(\frac{u_b}{L_b}\right)^2, \quad (10)$$

where, u_c , u_w , and u_b are the combined standard uncertainties associated with the contrast, the white, and the black measurement, respectively. This is because the respective measurements of white and black are entirely independent being measured by two luminance meters. Consider an example: The manufacturer quotes a relative uncertainty of measurement of $R_m \equiv U_m/L = 4\%$ for the luminance L of a CIE illuminant A at 100 cd/m^2 , which we will assume is an expanded uncertainty with a coverage factor of $k = 2$. They then say that the relative repeatability at this luminance level is $r_m \equiv s_m/L = 0.1\%$. Suppose also that the lowest the meter can read is 0.01 cd/m^2 and that the readout error is roughly $\delta L = 0.01 \text{ cd/m}^2$ because of the uncertainties associated with that last digit. Let's assume that the white luminance is $L_w = 130 \text{ cd/m}^2$. Suppose the black luminance measures $L_b = 0.51 \text{ cd/m}^2$. The contrast is $L_w/L_b = 255$, but what is the uncertainty in that contrast measurement?

If we only made a white luminance measurement, the uncertainty would be $R_m L_w$, that is, 4% of L_w . But when measuring contrast, we are going to combine the uncertainties of the white and black measurements. For this calculation, the standard uncertainty in the white luminance measurement is $u_w = (R_m/2)L_w = 2.6 \text{ cd/m}^2$, where the factor of two is from removing the effects of the $k = 2$ coverage factor. (Once we calculate the combined standard uncertainty of the contrast, then we will use a $k = 2$ coverage factor to obtain the final expanded uncertainty of contrast.) For the white measurement, the readout error is ignorable.

Naïvely speaking, the uncertainty in the black arises from the component of uncertainty associated with the instrument's calibration $R_m L_b$ and the component of uncertainty associated with the readout $\delta L = 0.01 \text{ cd/m}^2$, which for black is no longer ignorable. If that were true—that the relative uncertainty R_m stays unchanged for low-light level reading—then the standard uncertainty in the black measurement would be given by

$$u_b = \sqrt{\left(\frac{R_m}{2} L_b\right)^2 + (\delta L)^2}, \quad (11)$$

or $u_b = 0.014 \text{ cd/m}^2$. In doing this we have made the assumption that the repeatability is not a factor with which we have to be separately concerned, that is, we have assumed that u_b adequately accounts for repeatability. Now, from Eq. (10) the relative combined standard uncertainty (u_c/C) in the contrast is, naïvely,

$$\left(\frac{u_c}{C}\right)^2 = \left(\frac{dC}{C}\right)^2 = \left(\frac{u_w}{L_w}\right)^2 + \left(\frac{u_b}{L_b}\right)^2 = (0.020)^2 + (0.027)^2, \text{ or } u_c/C = 3.4\% \quad (12)$$

We should use a coverage factor of $k = 2$ so that the relative expanded uncertainty of the contrast measurement is $R_c = U_c/C = 6.8\%$. This calculation may seem adequate, but it probably is not. Here's why: *This naïve calculation hinges on the assumption that the $R_m = 4\%$ relative uncertainty of measurement of the instrument and its 0.1% relative repeatability remains the same for dark measurements as it is for the brighter measurements (such as its calibration point of the CIE Illuminant A). That is not necessarily true—in fact, it probably is not true. Unless the manufacturer can assure you of that fact or provide you with more uncertainty information that covers the lower-luminance levels, some attempt needs to be made to characterize the luminance meter for low light levels.* For example, suppose the detector has a noise of $s_n = 0.1 \text{ cd/m}^2$ about the zero signal, but any negative results would always be truncated to zero in the output of the instrument. For measurements of luminances of 100 cd/m^2 and above, that will permit a relative repeatability of 0.1% as stated in the specifications. The uncertainty in the white measurement is not affected by such noise, but the black is definitely affected. The combined standard uncertainty of black must add another component to account for this noise s_n . This is equivalent to including the measured repeatability of black as a component of the uncertainty in the result of a measurement:

$$u_b = \sqrt{\left(\frac{R_m}{2} L_b\right)^2 + (\delta L)^2 + s_n^2}, \quad (13)$$



or $u_b = 0.10 \text{ cd/m}^2$ and the relative contribution to the contrast uncertainty is $u_b/L_b = 0.20$. The noise in the black measurement now becomes the dominant source of uncertainty in the contrast result. The uncertainty in the white measurement becomes ignorable by comparison ($u_b/L_w = 0.020$), and essentially all of the uncertainty in the contrast measurement comes from the black measurement: With a coverage factor of $k = 2$, the relative expanded uncertainty in the contrast measurement result becomes 40 %. This shows how important it is to understand the instrument's capabilities in making black measurements. However, there are further problems. In evaluating Eq. (13) we assumed that the relative uncertainty R_m doesn't change as the luminance decreases. Usually, the uncertainty of an instrument decreases with the level of the signal measured—this is in addition to any readout errors encountered for low-level measurements (δL). Thus, before an uncertainty in a contrast measurement can be evaluated, the performance of the instrument in measuring low-level luminances must be provided or determined. See the appendix A6 Detector Linearity Diagnostics for some pointers on testing for low-light-level measurement capabilities.

When One Luminance Meters Is Used: The uncertainty formulation to this point has depended upon the measurements being independent. If we are using a single luminance meter to measure both white and black, the measurement results are no longer entirely independent of one another. Consider: Suppose the calibration of the luminance meter is very far from what it should be, let's say it is 25 % low; that is, a luminance $L_w = 100 \text{ cd/m}^2$ would be measured at $L'_w = 75 \text{ cd/m}^2$. But both the white and black measurement would be off by the same factor ($\alpha = 0.75$) and would not be independent, so that the ratio of the two in a contrast measurement could be rather accurate. The above formalism in Eq. (10) would predict a combined standard uncertainty of 35 %. But our intuition tells us that if $L'_w = \alpha L_w$ and $L'_k = \alpha L_k$, then the ratio $C = L_w/L_k = L'_w/L'_k$ is the same.

A11 SIGNALS, COLORS, AND PATTERN GENERATION

In order to make this document be applicable to as many display technologies as possible, only some general remarks will be made concerning signal generation. The pixel responds to a driving stimulus. That driving stimulus has voltage and timing characteristics that can be critical to the display's performance. Depending upon the display technology, that driving stimulus can originate as an analog voltage such as that provided to an RGB CRT monitor, or it can be a bit-level specified at a pixel location for a digital monitor associated with a computer's digital interface. At what point in the generation of the image on the display the user can access and control the driving stimulus cannot be entirely specified for all technologies. For example, gaining access to the signals driving a laptop computer display may be difficult. Even if we could get at those signals there is a risk that the loading of our measurement system's impedance might change the character of the signals and affect the displayed image. Suffice it to say that if a signal generator of some sort drives the display, that signal generator cannot create artifacts that influence any of the measurements specified in this document. To the extent the user has control of the driving stimulus, that driving stimulus cannot be inadequate in any way so that the measurements specified in this document are affected by the performance of the user-provided driving stimulus. For example, consider an analog signal generator: The voltage levels must be sufficiently accurate that they do not adversely influence the luminance levels of the pixels. Further, the transition times between voltage levels must be sufficiently fast so that no luminance artifacts can be measured associated with any two neighboring pixels which are caused by the signal generator. Therefore, when the user of this document is required to provide the driving stimulus for the display, the adequacy of that driving stimulus is the responsibility of the user. Any reporting should include the specifications and characteristics of any external generator if used.



A12 IMAGES AND PATTERNS FOR PROCEDURES

We provide a pattern-specification code for a number of patterns used in testing displays. These patterns in their individual pixel arrays are available at <https://doi.org/10.55410/1gam8989>. Commercial vendors supply similar patterns that can determine the pixel array (resolution) of the computer display being tested and conform the patterns to that resolution as well as making them conveniently selectable.

A12.1 TARGET CONSTRUCTION AND NAMING

Targets (a target can be a pattern or an image) can be employed to setup the display if the manufacturer does not provide specifications to do so or if the specified manufacturer's setup is found to be inadequate for the use of the display. If the display provides adjustments of, say, contrast, the objective would be to adjust for the visibility of the greatest number of gray levels near white and black while maintaining a natural look. It is generally found that human faces provide a tighter adjustment if such targets are appropriate to the task. In some scenes and faces there is a 32 level gray scale at the bottom and top of the screen and concentric boxes of the gray-scale ends on both sides.

A12.1.1 RENDERING GRAY AND COLOR LEVELS:

DIGITAL LEVELS IN SOFTWARE: When we speak of an eight-bit digital display, we know that there can be as many as $2^8 = 256$ levels for each primary color or that there are 256 gray levels to which the pixels can be set. This $N = 256$ is an ordinal number where 256 refers to white (the pixel or subpixel is turned to its maximum value or fully-on) and 1 refers to black (the pixel or subpixel is turned to its minimum value). However, when speaking about the actual command levels or bit levels in software or hardware, we often speak of 0 for black and 255 for white or for the color primary set to fully-on. The level number (the ordering number or index) goes from 1 to 256 but the values of the command or bit levels associated with those designated level indices go from 0 to 255. Thus, the black level is the first (command or bit) level and has a value of zero in software. The white or fully-on color-primary level is the 256th level and has a value of 255 in software. Thus, the numeric label or index for the level is not the same as the actual bit level or command level used in the software. When we say "level," "gray level," "color level," "red level," etc., we are referring to the command level or bit level in the software. When we say "level one," "the first level," "the nth level," etc. we are referring to the index number, an ordinal number.

In making some tests on displays, we often don't measure all the available levels, but we often select approximately evenly spaced levels that are a subset of the complete number of levels. Thus, we need to be careful when discussing levels; do we mean the ordering-level number index or the bit-level (or command-level) number? For example, if we select nine levels from the 256 levels, we are thinking in terms of ordinal numbers, numbers that order things. The first level is black and corresponds to a bit or command level of zero. Level nine is white (or fully-on primary color) and corresponds to a bit level of 255 for our eight-bit example. We sometimes confuse the index with the value of the level. Here is a specification for how to select a subset of M levels from a set of N available levels:

N is the number of available gray or color levels. For example, with an eight-bit scale, $N = 2^8 = 256$. For a ten-bit display, there are 1024 levels, and for a 12-bit display, there are 4096 levels.

$n = 1, 2, \dots, N$ is an *index* for a particular gray or color-primary level for the full gray scale or color scale. Level $n = N$ refers to white or a fully-on primary color, and level $n = 1$ refers to black.

Thus, $L_1 = L_K$ is black, and $L_N = L_W$ is white.

$w = N - 1$ is the bit level or command level associated with white or a maximum color primary; for the eight-bit scale, $w = 255$. The black bit level is 0.

M is the number of levels extracted from the complete set of N levels. We will often use 9, 17, 33, etc. levels (in the past we often used 8, 16, and 32 levels).

$j = 1, 2, \dots, M$ is the *index* for the extracted levels, the level number such as level 1, level 6, etc.

ΔV is the average spacing between extracted levels: $\Delta V = (N - 1)/(M - 1) = w/(M - 1)$ and may not be an integer.

$V_j = \text{int}[(j - 1) \Delta V] = 0, \text{int}(\Delta V), \text{int}(2\Delta V), \dots, w$ are the bit levels used for the extracted M levels. For an eight-bit display $V_M = 255$ $V_W = w$ for white or fully-on color primary and $V_K = V_1 = 0$ for black.

$\Delta V_j = V_j - V_{j-1}$, $j = 2, 3, \dots, M$, is the spacing between the extracted levels and will not be the same for all the j , in general.

To summarize:

Black: $V_1 \equiv V_K \equiv 0$ ($= 0$ usually, for 8-bit displays) produces black $L_1 \equiv L_K$.

White: $V_M \equiv V_W \equiv w$ ($= 255$ for 8-bit displays) produces white $L_M \equiv L_W$.



Table 1 shows a number of extracted levels from an eight-bit display. You will note the $M = 9, 17, 33$, and 65 sets are more evenly spaced than the $8, 16, 32$, and 64 level scales.

The levels found in the $M = 65$ set are also replicated in the $9, 17$ and 33 level sets as can be seen by following the color coding of the cells in the table. This kind of replication does not occur for the $8, 16, 32$, and 64 level sets. Because of this replication, some grayscale or color-scale patterns can be created with 33 levels and used for both the 17 and 9 level-scale measurements. (See the spreadsheet Scale-Levels.xls to calculate various scales not supplied in the accompanying table.)

ANALOG SIGNAL

LEVELS: For analog signals, if V_w is the white or fully-on color primary signal level and V_k is the black signal level, then for M evenly spaced levels the signal step size is $\Delta V = (V_w - V_k)/M$ and the selected signal levels are $V_j = V_k + (j - 1)\Delta V$, for $j = 1, 2, \dots, M$.

Table 1. M levels extracted from $N = 256$ levels.

$M = 8$ $\Delta V = 36.4$			$M = 9$ $\Delta V = 31.9$			$M = 16$ $\Delta V = 17$			$M = 17$ $\Delta V = 15.9$			$M = 32$ $\Delta V = 8.23$			$M = 33$ $\Delta V = 7.97$			$M = 64$ $\Delta V = 4.05$			$M = 65$ $\Delta V = 3.98$		
j	V_j	ΔV_j	j	V_j	ΔV_j	j	V_j	ΔV_j	j	V_j	ΔV_j	j	V_j	ΔV_j	j	V_j	ΔV_j	j	V_j	ΔV_j	j	V_j	ΔV_j
1	0		1	0		1	0		1	0		1	0		1	0		1	0		1	0	
2	36	36	2	31	31	2	17	17	2	15	15	2	8	8	2	7	7	2	4	4	2	3	3
3	72	36	3	63	32	3	34	17	3	31	16	3	16	8	3	15	8	3	8	4	3	7	4
4	109	37	4	95	32	4	51	17	4	47	16	4	24	8	4	23	8	4	12	4	4	11	4
5	145	36	5	127	32	5	68	17	5	63	16	5	32	8	5	31	8	5	16	4	5	15	4
6	182	37	6	159	32	6	85	17	6	79	16	6	41	9	6	39	8	6	20	4	6	19	4
7	218	36	7	191	32	7	102	17	7	95	16	7	49	8	7	47	8	7	24	4	7	23	4
8	255	37	8	223	32	8	119	17	8	111	16	8	57	8	8	55	8	8	28	4	8	27	4
			9	255	32	9	136	17	9	127	16	9	65	8	9	63	8	9	32	4	9	31	4
						10	153	17	10	143	16	10	74	9	10	71	8	10	36	4	10	35	4
						11	170	17	11	159	16	11	82	8	11	79	8	11	40	4	11	39	4
						12	187	17	12	175	16	12	90	8	12	87	8	12	44	4	12	43	4
						13	204	17	13	191	16	13	98	8	13	95	8	13	48	4	13	47	4
						14	221	17	14	207	16	14	106	8	14	103	8	14	52	4	14	51	4
						15	238	17	15	223	16	15	115	9	15	111	8	15	56	4	15	55	4
						16	255	17	16	239	16	16	123	8	16	119	8	16	60	4	16	59	4
									17	255	16	17	131	8	17	127	8	17	64	4	17	63	4
												18	139	8	18	135	8	18	68	4	18	67	4
												19	148	9	19	143	8	19	72	4	19	71	4
												20	156	8	20	151	8	20	76	4	20	75	4
												21	164	8	21	159	8	21	80	4	21	79	4
												22	172	8	22	167	8	22	85	5	22	83	4
												23	180	8	23	175	8	23	89	4	23	87	4
												24	189	9	24	183	8	24	93	4	24	91	4
												25	197	8	25	191	8	25	97	4	25	95	4
												26	205	8	26	199	8	26	101	4	26	99	4
												27	213	8	27	207	8	27	105	4	27	103	4
												28	222	9	28	215	8	28	109	4	28	107	4
												29	230	8	29	223	8	29	113	4	29	111	4
												30	238	8	30	231	8	30	117	4	30	115	4
												31	246	8	31	239	8	31	121	4	31	119	4
												32	255	9	32	247	8	32	125	4	32	123	4
															33	255	8	33	129	4	33	127	4
																		34	133	4	34	131	4
																		35	137	4	35	135	4
																		36	141	4	36	139	4
																		37	145	4	37	143	4
																		38	149	4	38	147	4
																		39	153	4	39	151	4
																		40	157	4	40	155	4
																		41	161	4	41	159	4
																		42	165	4	42	163	4
																		43	170	5	43	167	4
																		44	174	4	44	171	4
																		45	178	4	45	175	4
																		46	182	4	46	179	4
																		47	186	4	47	183	4
																		48	190	4	48	187	4
																		49	194	4	49	191	4
																		50	198	4	50	195	4
																		51	202	4	51	199	4
																		52	206	4	52	203	4
																		53	210	4	53	207	4
																		54	214	4	54	211	4
																		55	218	4	55	215	4
																		56	222	4	56	219	4
																		57	226	4	57	223	4
																		58	230	4	58	227	4
																		59	234	4	59	231	4
																		60	238	4	60	235	4
																		61	242	4	61	239	4
																		62	246	4	62	243	4
																		63	250	4	63	247	4
																		64	255	5	64	251	4
																		65	255	4	65	255	4



A12.1.2 GRAY LEVELS IN PERCENT OF WHITE:

Several patterns and several of the gray shades or colors in the setup targets refer to percentages of white or saturated colors. Such levels (sometimes called command levels) come from the analog signal world where use is made of a gray scale based upon an analog signal in percent of the difference between the white signal level and the black signal level. An accurate correspondence between the percent-of-white gray-shade and the 256-level gray shade cannot be obtained to perfectly match the percentages desired in the pattern. We propose the following rule to get approximate bit-levels in a $N = 256$ gray scale with white specified by $w = N - 1$ and 0 for black: The bit level V associated with the percentage p expressed as a fraction is

$V = \text{int}(wp) = \text{int}(255 \times \text{percentage}/100\%)$. This amounts to rounding all the fractional values down. See Table 2 for the various levels used in the patterns.

Table 2. Percent vs. Bit Level					
%	Level	%	Level	%	Level
0	0	40	102	75	191
5	13	48	122	80	204
10	25	50	127	85	216
15	38	51	130	90	229
20	51	53	135	95	242
25	63	60	153	100	255
30	76	70	178		

A12.1.3 TARGET CONFIGURATION AND FILE NAMING CONVENTIONS

In Table 3, Locations and Dimensions of Objects, we present examples the details involved in creating the simple patterns for setup. In the Table 4, File and Pattern Naming Conventions, we show how we name the patterns used.

Table 3. Locations and dimensions of major objects.

Pixel Array	640x480	800x600	1024x768	1280x1024	1600x1200	1920x1200
Array Name	VGA	SVGA	XGA	SXGA	UGA	UXGA
Diagonal, D	800	1000	1280	1639.2	2000	2264.2
H	640	800	1024	1280	1600	1920
V	480	600	768	1024	1200	1200
N_T (square px = px ²)	307 200	480 000	786 432	1 310 720	1 920 000	1.6
Values often adjusted to reflect even numbers via $2\text{int}(x/2)$:						
3% $d(r)$	24 (12)	30 (14)	38 (18)	48 (24)	60 (30)	66 (32)
5% $d(r)$	40 (20)	50 (24)	64 (32)	80 (40)	100 (50)	112 (56)
20% (1/5) Box (px ²)	110	138	177	228	277	303
Top left corner of centered 20% (1/5) box:	(256, 192)	(320, 240)	(410, 308)	(512, 410)	(640, 480)	(768, 480)
Corner of highlight box (30 px square)	(304, 224)	(380, 280)	(487, 359)	(608, 480)	(760, 560)	(912, 552)
Box	% of A	Area Obtained (Location of top left corner in parentheses.)				
5%	0.25%	32 x 24	40 x 30	50 x 38	64 x 50	80 x 60
		(304, 228)	(380, 286)	(488, 366)	(608, 488)	(760, 570)
10%	1.00%	64 x 48	80 x 60	102 x 76	128 x 102	160 x 120
		(288, 216)	(360, 270)	(462, 346)	(576, 462)	(720, 540)
15%	2.25%	96 x 72	120 x 90	152 x 114	192 x 152	240 x 180
		(272, 204)	(340, 256)	(436, 328)	(544, 436)	(680, 510)
20%	4.00%	128 x 96	160 x 120	204 x 152	256 x 204	320 x 240
		(256, 192)	(320, 240)	(410, 308)	(512, 410)	(640, 480)
25%	6.25%	160 x 120	200 x 150	256 x 192	320 x 256	400 x 300
		(240, 180)	(300, 226)	(384, 288)	(480, 384)	(600, 450)
30%	9.00%	192 x 144	240 x 180	306 x 230	384 x 306	480 x 360
		(224, 168)	(280, 210)	(360, 270)	(448, 360)	(560, 420)
40%	16.00%	256 x 192	320 x 240	408 x 306	512 x 408	640 x 480
		(192, 144)	(240, 180)	(308, 232)	(384, 308)	(480, 360)
50%	25.00%	320 x 240	400 x 300	512 x 384	640 x 512	800 x 600
		(160, 120)	(200, 150)	(256, 192)	(320, 256)	(400, 300)
60%	36.00%	384 x 288	480 x 360	614 x 460	768 x 614	960 x 720
		(128, 96)	(160, 120)	(206, 154)	(256, 206)	(320, 240)
70%	49.00%	448 x 336	560 x 420	716 x 536	896 x 716	1120 x 840
		(96, 72)	(120, 90)	(154, 116)	(192, 154)	(240, 180)
80%	64.00%	512 x 384	640 x 480	818 x 614	1024 x 818	1280 x 960
		(64, 48)	(80, 60)	(104, 78)	(128, 104)	(160, 120)
90%	81.00%	576 x 432	720 x 540	920 x 690	1152 x 920	1440 x 1080
		(32, 24)	(40, 30)	(52, 40)	(64, 52)	(80, 60)



Table 4. File and pattern naming conventions.

PATTERN_####x####.TYP	
NUMBERING CONVENTIONS: (To specify colors and gray levels of pattern or component parts.)	
#-# ##-##	Two numbers separated by a dash: The first number refers to the number of levels used in the pattern or a sequence of patterns, e.g., 8, 9, 16, 17, 33. The second number refers to the level number of the pattern. Thus FS33-15 refers to a full-screen gray of the fifteenth level in a 33-level sequence of full-screen patterns, which has a full-screen gray level of 111 (refer to Table 1).
##p	Two-digit number with trailing lower-case "p" refers to the level in percent of maximum luminance (e.g., FS25p, a full-screen gray at 25%, FG50p is a green full screen at 50%).
###	Three-digit number (e.g., 123) refers to the ### 8-bit level out of 255 available levels, e.g., FS127 is a gray full screen at level 127 of 255; FB205 is a blue full screen at blue level 205.
###-###-###	Three three-digit numbers separated by dashes refers to a 24-bit RGB setting (e.g., F123-050-012 is a full-screen rust color with R=123, G=50, B=12 out of 255). Should a greater or lesser bit depth than 8 be required, the bit depth used for each color can be explicitly indicated by using the underscore character and a sufficient number of characters to accommodate the largest number; e.g., for 8 bits of red, 10 bits of green, 6 bits of blue use ###_8-####_10-##_6.
####-####- ####-N	Future use for displays with $N = 10$ bit, 12 bit, and higher. Should we ever see 16-bit displays, use hex notation with a designation of "16h" for N , where #### ranges from 0 to FFFF.
FILE PIXEL ARRAY SPECIFICATION	
_####x####	(Underscore separator) Horizontal number of pixels \times Vertical number of pixels ($H \times V$) using at least four digits for each number; e.g., FW_1920x1080.PNG or FK_0640x0480.PNG.
TYPE (TYP) CONVENTIONS:	
PDF	Adobe Portable Document Format®.
PNG	Portable Network Graphics (as of this writing see http://www.libpng.org/pub/png/) is in the public domain and is used for most all bit-mapped images and patterns connected with this document.
PPT	Microsoft PowerPoint®.
DESCRIPTION CONVENTIONS	
<ol style="list-style-type: none"> When we say a box is a certain percentage of the diagonal, e.g., 20 %, we are implying the box aspect ratio is the same as the aspect ratio of the screen, e.g., $0.20H \times 0.20V$, as best as can be generated at the pixel level. When speaking of the 10 % periphery, we mean the imaginary box made at $0.10H$ and $0.10V$ away from the outer edges of the screen. Usually this is used to locate measurement points symmetrically placed about the center of the screen. In the case of nine measurement points, they will be at the center and then at the corners and centers of the 10 % periphery box. In the case of 25 points, they will be at the nine points and symmetrically between them making a 5×5 symmetrical matrix. 	
PATTERN NAMING CONVENTIONS (Format at left, examples at right in first column):	
$nXn?$...	CHECKERBOARD: Specified with color = ? in the upper left corner (K or W assumes a black and white checkerboard). If a color designation is left off, it will be a white-black checkerboard with white in the upper left corner. C specifies alignment circles in all rectangles, C# ($\# < n$) means symmetrically placed, but not in all rectangles.
3X3K	3×3 checkerboard with black upper left corner.
4X4GM	4×4 checkerboard with green at upper left alternating with magenta.
2X2WC	2×2 checkerboard with white in upper left corner and alignment circles centered in all rectangles.
5X5KC9	5×5 checkerboard with alignment circles in nine locations at the center, corners, and centers of the edges.
AT..., P, N	ALIGNMENT TARGETS: Provided to identify locations of cardinal points on the display surface and are supplied in positive (P, dark lines on white) or negative (N, light lines on black) formats.
AT01P, N	Alignment target #01 in positive (negative) format: Concentric circles of 5 % and 3 % of screen diagonal are placed at nine locations around the 10 % periphery, and 3 % circles are placed at 25 positions. Boxes of 5 % size are placed on a cross pattern and on the periphery. Diagonal lines connect the corner measurement points.



AT02P	Alignment target #02 in positive format: Crosshairs and circles located at the center of a 3x3 matrix.
CAT...	CENTERING & ALIGNMENT TARGETS: Provided also in bit mapped versions where the center target is a specified diameter and does not scale with the image size.
CAT01A	This is the non-bitmapped version of CAT01 (see below) where the center target is replaced with a crosshair.
CBV, CBH ...	COLOR BARS VERTICAL, HORIZONTAL: If no level is specified via a number designation (##) then it is assumed at 100 % level.
CBV50	Color bars at 50 % level.
CBV-32SH01	Vertical color bars at 100 % saturation with 32-level horizontal gray scales, pattern #01.
CHRT...	Color charts having multiple colored rectangles.
CHRT01-1,..., 5	Special selection of colors placed in different sequences.
CINV...	COLOR INVERSION targets:
CINV01	Color inversion target #01 where eight gray levels are displayed in a pie pattern placed on a 50 % (127/255) background. Within each pie piece is a colored pie composed of the gray level plus a 36-bit level increase in red, then green, then blue—except for the white pie that has the same color pie as the previous gray level (6) pie piece. The main pie pattern is reduced in size and replicated at all nine points. The pattern can be used for spotting color and gray-scale inversions. See Reference 2.
CS, CSS, CCPL,...	COLOR SCALES:
CSSR##, G, B	Color scales snaking from maximum red (or green or blue, etc.) to black displaying ## evenly spaced colors.
CSGRAD01	Gradients from white to black through the saturated primary and secondary colors (also two flesh tones).
CSD01	Discrete color scales from white to black through the saturated primary and secondary colors.
CCPLR, B, G##, (#)	Color scales for constant picture level: 33 (and 9) level color-scale series for constant picture level where the center box interchanges with all the other box colors. Originally developed for global-dimming displays with automatic picture level control: Measure the center box, use a frustum mask to avoid veiling glare in the detector. CCPL## patterns marked with an asterisk (*) in the lower right corner are the patterns for a 17 level subset. Patterns marked with a double dagger (‡) are the patterns for a 9 level subset.
...CX...	Concentric Boxes
RCXK256	Red concentric boxes from a black center to a red periphery in 256 steps.
RCXR256	Red concentric boxes from a red center to a black periphery in 256 steps.
QCXQ256	Quad concentric boxes from RGBW at center to a black periphery in 256 steps.
QCXK256	Quad concentric boxes from a black center to RGBW periphery in 256 steps.
DCXS256	Dual concentric boxes in 256 gray-shade steps.
DCXR256	Dual concentric boxes in 256 red steps.
D...	Dual patterns having two parts usually inverses of each other (see "...CX...") above.
F...	FULL-SCREEN color: <ol style="list-style-type: none"> 1. W=white, K=black, R=red, G=green, B=blue, C=cyan, M=magenta, Y=yellow, 2. S=gray scale and denotes level and intended shade. Because patterns FS... may have their level written in the lower left hand corner, the file size for FS0 may be slightly different from FK and FS9–9 may be slightly different from FW, and so forth, but only because of the file name that may appear with the pattern. This writing, or something similar, may be included because it is not often immediately obvious exactly what gray level is being displayed when using a full-screen display mode. 3. AC# (e.g., #=5, 9, 25) indicates that # alignment circles are included and placed symmetrically centered in rectangles as if there were a checkerboard present (e.g., if #=9, then a 3x3 checkerboard is imagined; if #=25, then a 5x5 is imagined). Adding "L10" means that 10 % (of diagonal) locations are used in the periphery (not at imaginary checkerboard center locations). Any other circle arrangements (such as a weighting near center) will be given unique names. 4. SH## = harmonized gray scale (see table in § A12.1.1 for details) for ## total levels.



FW, FK, FG, FY	Full-screen white, black, green, yellow.
F###-###-###	Full-screen RGB color ###-###-###.
F123-207-035	Full-screen RGB color with R=123/255, G=207/255, B=35/255.
FG3	Full-screen green at level (or intended color) of 3 out of 8 (73/255).
FM-13	Full-screen magenta at level (or intended color) of 13 out of 16 (204/255).
FWC9	Full-screen white with nine alignment circles centered in an imaginary 3×3 checkerboard.
FWC9L10	Full-screen white with nine alignment circles placed at center and the remaining eight at the 10 % (<i>H</i> & <i>V</i>) periphery locations.
FS5	Full-screen gray scale (level or intended shade) for level 5 of 8 shades (182/255).
FS50	Full-screen gray scale (level or intended shade) of 50 % (127/255) = FS127 = F127-127-127.
FSH33-07	Full-screen gray level 7 of 33 harmonized levels
FS067	Full-screen gray scale (level or intended shade) for level 67/255.
Face...	Face patterns: Computer simulated faces of different flesh tones. Matrix notation identifies the face 11 is the upper left and 24 is the bottom right based upon the location in Faces pattern and FacesCS pattern.
FaceCC##	Face ## at center and corners on black background.
FaceCS##	Face ## with resolution targets and color ramps and percent gray scales.
FaceFull##	Full face with 50 % gray (127/255) sides.
FaceFullCS##	Full Face with RGB ramps at sides and gray-scale ramps above and below.
FaceFullGS##	Full Face with gray-scale ramps at sides and above and below.
FaceMX##	A matrix of identical faces that covers the screen.
Faces	All faces on 50 % gray background.
FacesCS	All faces with RGBCMY and gray-scale ramps.
FigsAll	All figures holding spheres against picture backdrop.
FacesSL	All faces with strong side lighting on black background.

G...	GEOMETRIC patterns: Often these will be line patterns. Adding “ M ” to the end of the name denotes markers are included to identify many of the measurement points including the center. Often, when the pattern is complicated, the center is always identified. Adding “ H ” denotes the use of heavier lines. For the pixel generated equivalent of these, see P#L_n×m .
G#X#WK	Rectangular #×# grid in both the horizontal and vertical directions from edge to edge with white (or other color) lines on black (or other color).
G11X11WKM	11×11 grid of white lines on black with markers included.
GV##WKH	## vertical heavy white lines on black from edge to edge (left to right).
GH##WK	## horizontal white lines on black from edge to edge (top to bottom).
H##	HALATION pattern, black centered rectangle in white background. ## refers to linear size of rectangle in percent of diagonal. H20 is a 20 % black rectangle in white, a shorthand equivalent to pattern X20KW.
H05	Halation pattern of a centered black rectangular box 0.05 <i>H</i> ×0.05 <i>V</i> on a white background.
INTRO	INTRODUCTION image and title page with specifications for creation of gray scale.
I...	IMAGE , bit-mapped, of various subjects.
IHF01	Image of human face #01.
INS01	Image of natural scenes #01.
IHFCB01	Image of human face and color bars #01.
L##	LOADING pattern, white centered rectangle in black background. ## refers to linear size of rectangle in percent of diagonal. L20 is a 20 % white rectangle in black, a shorthand equivalent to pattern X20WK.
L60	Loading pattern of a centered white rectangular box 0.60 <i>H</i> ×0.60 <i>V</i> on a black background.



P...	<p>PIXEL patterns: It is not always possible to assure exactly even spacing and centering of lines and dots because of the discreteness of the pixel array. In general, these types of patterns cannot be properly reproduced with slide presentation software.</p> <p>PG = pixel grille patterns in horizontal H or vertical V directions, $n \times m$ specifies an $n \times m$ pixel grille with n pixels in one color and m pixels in another color. The color is specified after the $n \times m$ descriptor. No color designation implies white and black pixels used starting with white in the left or top position. More than two lines can be specified.</p> <p>Pn\timesn without the "G" implies a pixel checkerboard of $n \times n$ pixels. If no color specifications are made, a white-black checkerboard is assumed with white in the upper left corner. Otherwise, the first color specified after the notation is in the upper left corner.</p> <p>PLn\timesm, P2Ln\timesm, P#Ln\timesm ... = grids of one, two, and # pixels wide lines in an $n \times m$ pattern from edge to edge and top to bottom. Usually this will be single or double pixel lines. White lines on black are assumed unless a color designation is supplied after the $n \times m$ specification to denote the line color on the background color.</p> <p>PD, P2D, ... = dots of one, two, ... pixels in horizontal and vertical size (i.e., square clusters) placed in a $n \times m$ grid pattern. White dots on black are assumed unless a color designation is supplied after the $n \times m$ specification to denote the dot color on the background color. Usually, these dots will have the size of one or two pixels.</p>
PGV2X3GR	Vertical 2 \times 3 pixel grille, 2 green pixels by 3 red pixels.
PGH3X3	Horizontal 3 \times 3 pixel grille, 3 white pixels (at top) by 3 black pixels.
PGV1X1	Vertical 1 \times 1 pixel grille of white (at left) and black pixels.
PGH3X2X1GKW	Pixel horizontal grille, 3 green pixels by 2 black pixels by 1 white pixel.
PL11X11	Single pixel lines in an 11 \times 11 grid pattern, white lines on black assumed.
PL11X11KW	Single pixel lines in an 11 \times 11 grid pattern, black lines on white.
PD11X11GK	Single pixel green dots on black in an 11 \times 11 matrix pattern.
P2L11X11G	Double pixel green lines on black (assumed) in an 11 \times 11 grid pattern.
P1X1, K	Single-pixel checkerboard with white (black) pixel in upper left corner. P1X1 and P1X1W are the same.
P3X3YM	3 \times 3 pixel checkerboard composed of yellow and magenta pixels starting with yellow in the upper left corner.
Q...	Quad color patterns using RGBW (see "...CX...").
QCXQ256	Quad concentric boxes from RGBW at center to a black periphery in 256 steps.
QCXK256	Quad concentric boxes from a black center to RGBW periphery in 256 steps.
RT...	REFLECTION TARGETS: Targets #01 and #02 are based upon symmetrized versions of the reflection targets specified in the ISO 9241 series where 80 % loading of white or black is suggested. See Reference 3.
RT01AP	Reflection target #01-A in positive format (background of white with black rectangles).
RT02BN	Reflection target #02-B in negative (background of black with white rectangles).
S, SCPL, SE, SCX, SR..., SS..., etc.	GRAY-SCALE SHADE patterns: S means gray-scale pattern, SE means gray-scale ends, SCX is concentric boxes, SS is snaking, SEL is elliptical scale pattern, SEB is a central boxes pattern in percent of gray scale. We use "S" to denote the level or the intended shade in the gray scale to avoid confusion with green.
SEB01	Grayscale ends of boxes from 0% to 30 % and 70 % to 100% in increments of 1% with levels designated in medium gray text on each side with narrow 32-level gray scales top and bottom.
SET01S###	Gray-scale ends displayed in pattern #01 on a background of a gray-level ###/255. Pattern #01 has two small horizontal gray scales at the top and bottom with four adjoining boxes of gray levels in white and four in black placed near the center having levels at 100 %, 95 %, 90 %, 85 % and 0 %, 5 %, 10 %, 15 %. See Reference 4.
SET01W	Grayscale ends pattern #01 on white.
SET01K	Grayscale ends pattern #01 on black.
SET02S50	Same as SET01S50 with added concentric boxes (32-level ends) top and bottom
SET03S50	Same as SET02S50 with added concentric boxes (32-level ends) left and right
SET04S50	Same as SET03S50 with added color ramps, 32-level scales, and white center box



SECX01K	Grayscale ends in centered concentric boxes, pattern #01, having the six levels at each end of the gray scale on a black background.
SECX01W	Grayscale ends in centered concentric boxes, pattern #01, having the six levels at each end of the grayscale on a white background.
SRAND01	256 level gray scale in randomized blocks of equal size.
SVP32S01	Grayscale ends pattern with 32 gray-levels in "V" pattern. Gray level ends are in concentric boxes covering six levels at both ends of the 32-level gray scale.
SXP32S01	Grayscale ends pattern with 32 gray-levels in "X" pattern. Gray level ends are in concentric boxes covering six levels at both ends of the 32-level gray scale.
SCXK64	Concentric boxes of 64 gray shades with black center to white perimeter.
SCXW64	Concentric boxes of 64 gray shades with white center to black perimeter.
SCXKW64	Concentric boxes of 64 gray shades with black center left side and white center right side.
SCX32KX	Concentric boxes of 32 gray shades with a 1/5 box of black at the center (can also have 33 shades and a 1/6 box is also allowed). The center black box is denoted with short blue lines in the corners.
SSW64	Snaking 64 gray shades from white upper left to black lower right.
SSW256	Snaking 256 gray shades from white upper left to black lower right.
SSKE	Snaking black end with 32 boxes from levels 0 to 31.
SSWE	Snaking white end with 32 boxes from levels 255 to 224.
SCPL## (SCPL#)	33 (and 9) level gray scale series for constant picture level where the center box interchanges with all the other box shades. Originally developed for global-dimming displays with automatic picture level control: Measure the center box, use a frustum mask to avoid veiling glare in the detector. SCPL## patterns marked with an asterisk (*) in the lower right corner are the patterns for a 17 level subset. Patterns marked with a double dagger (‡) are the patterns for a 9 level subset.
TXT..., P, N	TEXT TARGETS: Various text targets are supplied in positive (black text on white) or negative (white text on black) formats.
TXT01P	Text pattern #01 in positive format.
X##??	BOX , centered, ## % of diagonal in size with color of box (color = ?) specified and background (color = ?). Use underline separator for clarity if needed (?_?).
X20WB	20 % white box centered on blue screen.
X05B213R117	5 % blue 213/255 box centered on red 117/255 screen.
X05KW	5 % black box centered on white screen.

SPECIAL BIT-MAPPED TARGETS: (See Section A12.3)	
BUSY01	Pixel-specific composite pattern of different grilles, checkerboards, and blocks in gray.
BUSY01R	Same as BUSY01 but in red only.
BUSY01G	Same as BUSY01 but in green only.
BUSY01B	Same as BUSY01 but in blue only.
CAT01	Centering and alignment target with red arrows locating the direction toward the center and a 60-pixel diameter center target with red border (outside the 60-pixel target).
HICON01	30-pixel square white box at the center of a black screen for making highlight-contrast measurements.
VSMPTE133a	VESA adapted SMPTE RP 133 with single pixel checkerboards added.
VSMPTE133b	VESA adapted SMPTE RP 133 with single pixel checkerboards, noise patches, and text samples at various contrasts added.

1. The color inversion target CINV01 has been referred to as the Brill-Kelley chart and was first published by Michael H. Brill, "LCD Color Reversal at a Glance," *Information Display*, Vol. 16, No. 6, pp. 36, 37, June 2000, where a preliminary version of the target was inadvertently published. The corrected pattern (shown in this document) is noted in the erratum in Vol. 16, No. 10, p. 46, October 2000 of *Information Display*.
2. International Organization for Standards (ISO), 9241-7, Ergonomic requirements for office work with visual display terminals (VDTs), Part 7, Display requirements with reflections, 1997-02-15.



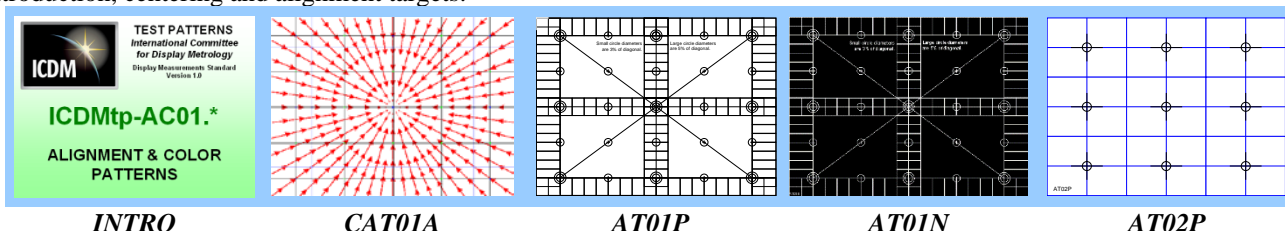
3. Pattern SET01W is a variation of a pattern used in ANSI/PIMA IT7.227-1998 Electronic Projection-Variable Resolution Projectors (PIMA is Photographic and Imaging Manufacturers Association, Inc.) and ANSI/NAPM IT7.228-1997 Electronic Projection-Fixed Resolution Projectors (NAPM is National Association of Photographic Manufacturers, now changed to PIMA). Patterns SET01S50 and SET01K are variations of patterns proposed to PIMA by the National Information Display Laboratory of the Sarnoff Corporation in Princeton, N.J., used by permission. We have added full 32-level gray scales at the top and bottom.

A12.2 SETUP TARGETS IN PATTERN COLLECTIONS

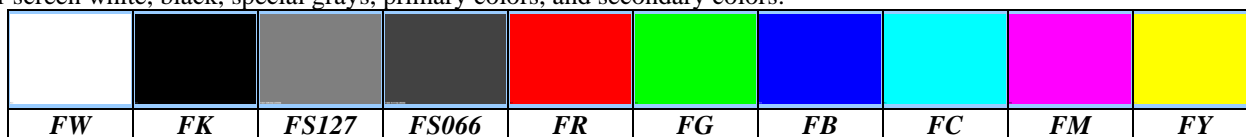
A variety of setup targets have been created for setting up the display, making demonstrations, and performing simple tests on the display. We have included an image of a human face and some synthetic human faces along with some natural scenes. We have found that gray scales are fine, as are color scales, for setting up displays when there is an adjustment in the contrast and brightness, etc. However, an image of a face will generally better limit the allowable ranges of setup conditions than gray or color scales alone. You will probably find that considerable adjustment is tolerated for some displays when looking at gray and color scales, even natural images of scenes; but the face will generally not allow as much adjustment of the settings. (Note: If you need to scale the entire set to another aspect ratio, in PowerPoint®, for example, use File/Page Setup.../ and select or define a new display format as needed.)

ICDMtp-AC01.* — Alignment & Color Patterns

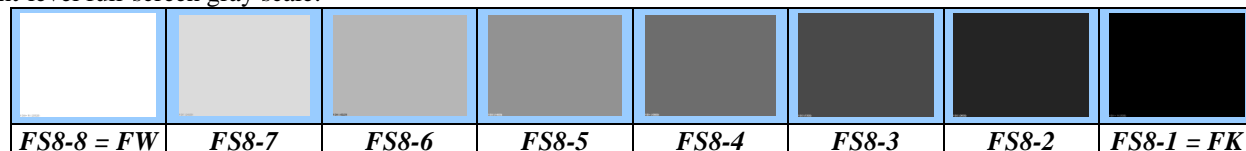
Introduction, centering and alignment targets:



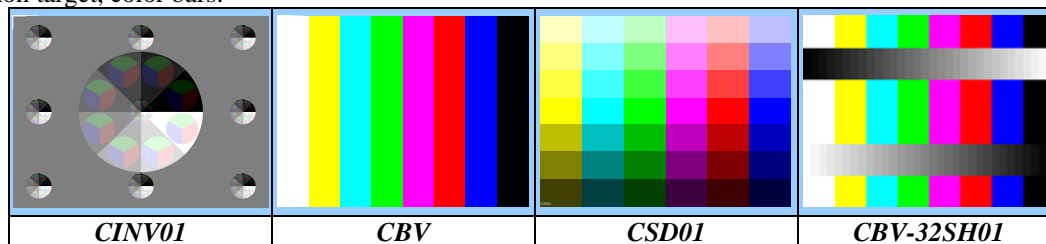
Full-screen white, black, special grays, primary colors, and secondary colors:



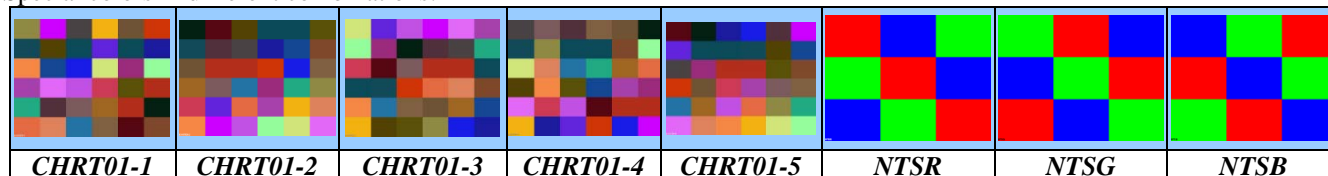
Eight-level full-screen gray scale:



Color inversion target, color bars:



Special colors in different combinations:





ICDMtp-HL01.* — Halation & Loading Patterns

Targets for manifesting halation (contamination of darks with surrounding light areas — use frustum mask).

<i>INTRO</i>	<i>H05</i>	<i>H10</i>	<i>H20</i>	<i>H30</i>	<i>H40</i>	<i>H50</i>	<i>H60</i>	<i>H70</i>	<i>H80</i>	<i>H90</i>	<i>FK</i>

Targets for manifesting loading (change in luminance with size of white area).

<i>L05</i>	<i>L10</i>	<i>L20</i>	<i>L30</i>	<i>L40</i>	<i>L50</i>	<i>L60</i>	<i>L70</i>	<i>L80</i>	<i>L90</i>	<i>FW</i>

ICDMtp-CB01.* — Checkerboard Patterns

<i>INTRO</i>	<i>2X2K</i>	<i>2X2W</i>	<i>2X2KC</i>	<i>2X2WC</i>	<i>FWC9</i>	<i>FKC9</i>
<i>3X3K</i>	<i>3X3W</i>	<i>3X3KC</i>	<i>3X3WC</i>	<i>4X4K</i>	<i>4X4W</i>	<i>4X4KC</i>
<i>4X4WC</i>	<i>5X5K</i>	<i>5X5W</i>	<i>5X5KC</i>	<i>5X5WC</i>	<i>6X6K</i>	<i>6X6W</i>
<i>7X7K</i>	<i>7X7W</i>	<i>8X8K</i>	<i>12X12K</i>	<i>16X16K</i>	<i>24X24K</i>	<i>32X32K</i>

ICDMtp-GC01.* Gray-Scale & Color-Scale Patterns

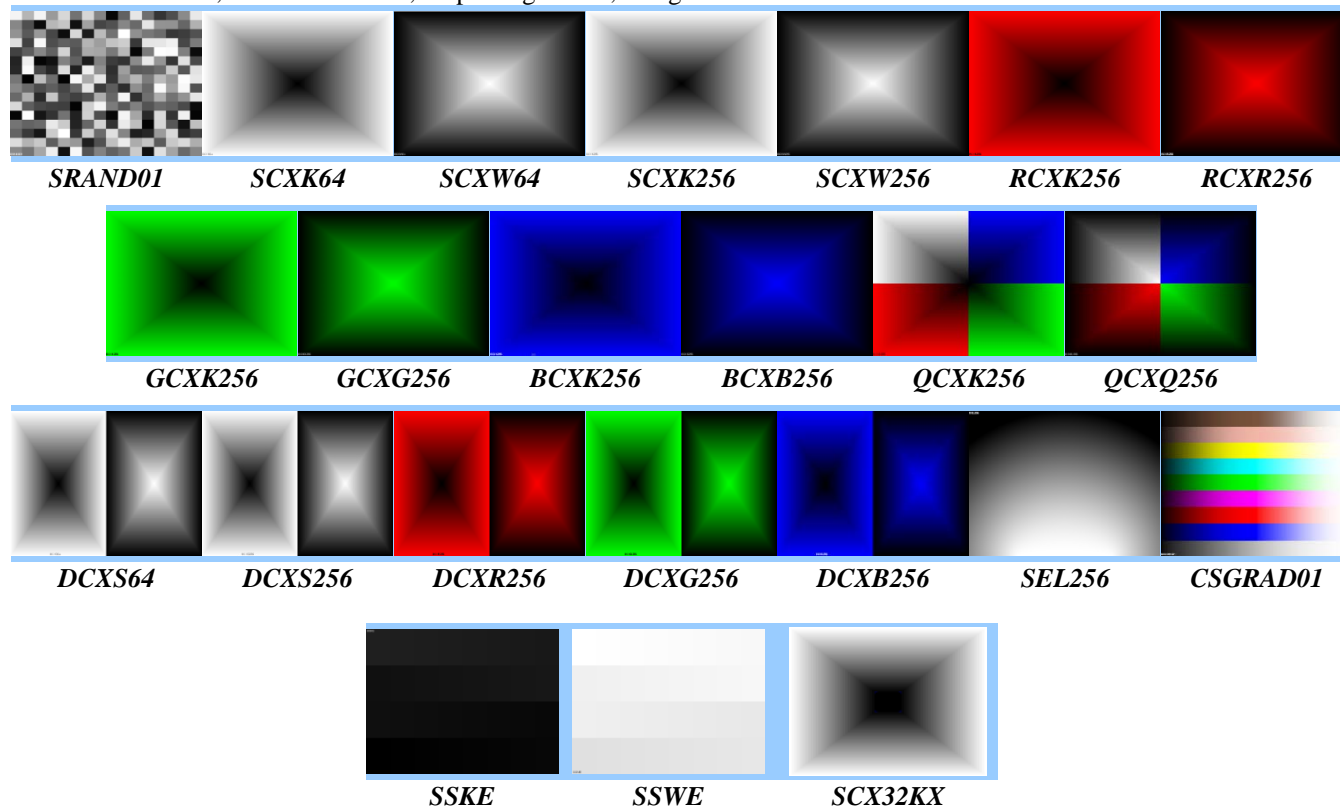
<i>INTRO</i>	<i>SXP32S01</i>	<i>SVP32S01</i>	<i>SECXK01</i>	<i>SECXW01</i>	<i>SEB01</i>	<i>SEK01</i>

Snaking gray shades with 32, 64, 128, and 256 levels:

<i>SSW32</i>	<i>CSSR32</i>	<i>CSSG32</i>	<i>CSSB32</i>	<i>SSW64</i>	<i>SSW128</i>	<i>SSW256</i>

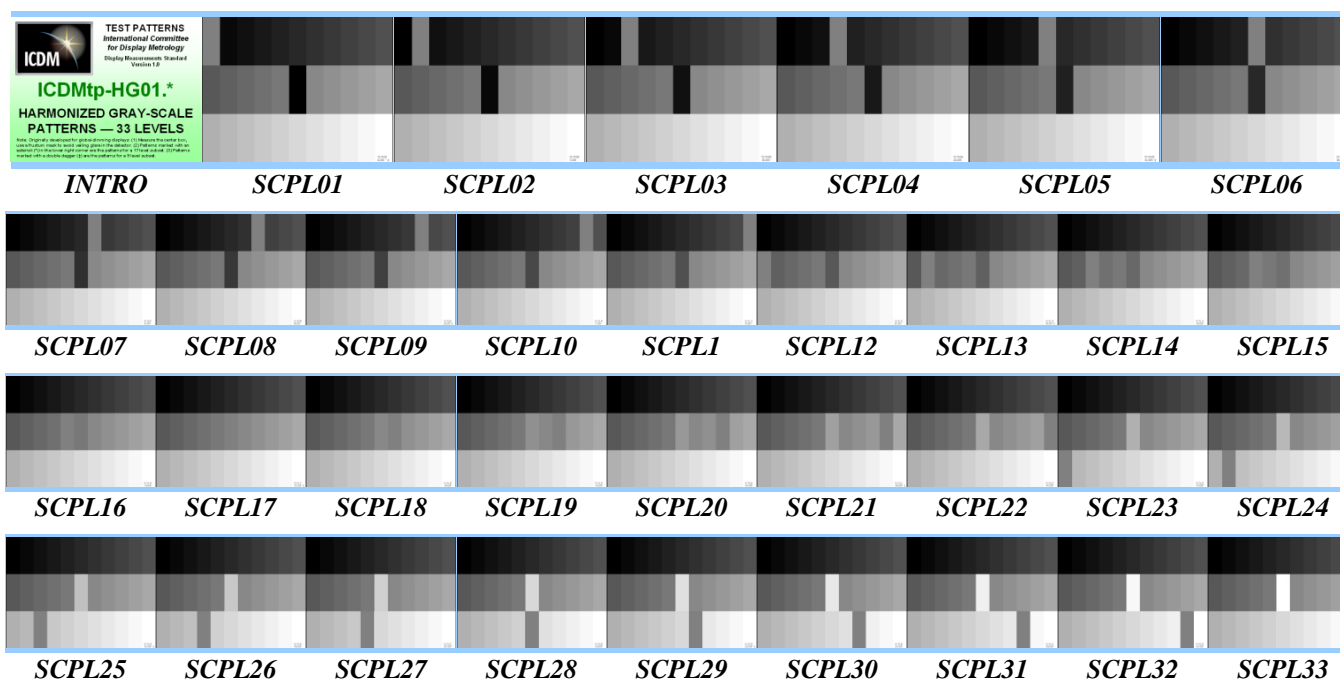


Random 256 levels, concentric boxes, elliptical gradient, and gradient bars:



ICDMtp-HG01.* — Harmonized Gray-Scale Patterns — 33 Levels:

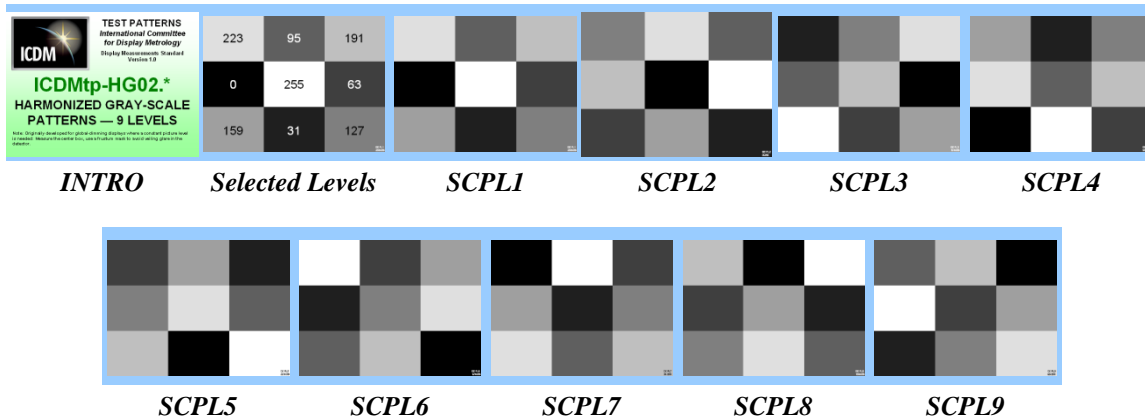
This pattern idea was originally developed for global-dimming and local-dimming displays: (1) Measure the center box, use a frustum mask to avoid veiling glare in the detector. (2) Patterns marked with an asterisk (*) in the lower right corner are the patterns for a 17 level subset. (3) Patterns marked with a double dagger (§) are the patterns for a 9 level subset. Not shown here are the similar primary-color renderings of these patterns: CCPLR##, CCPLG##, CCPLB##.



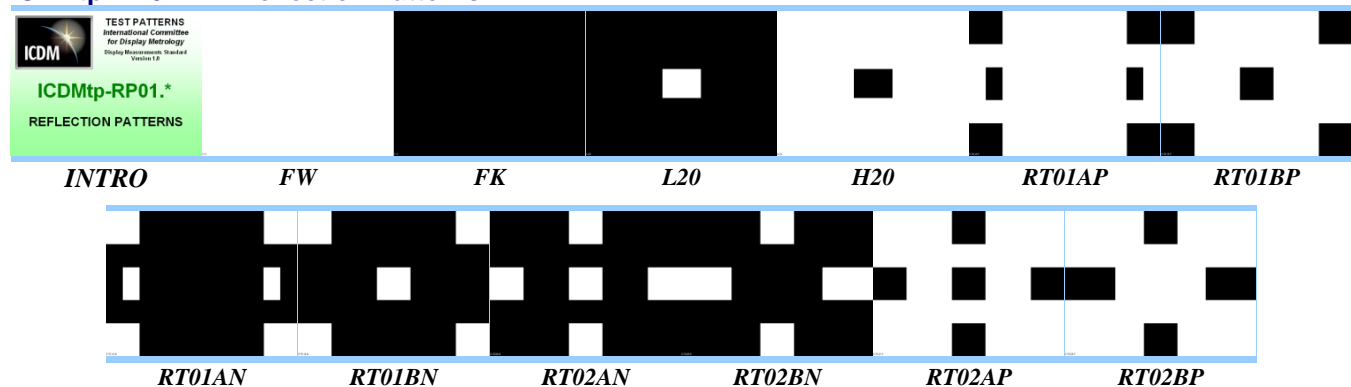


ICDMtp-HG02.* — Harmonized Gray-Scale Patterns — 9 Levels:

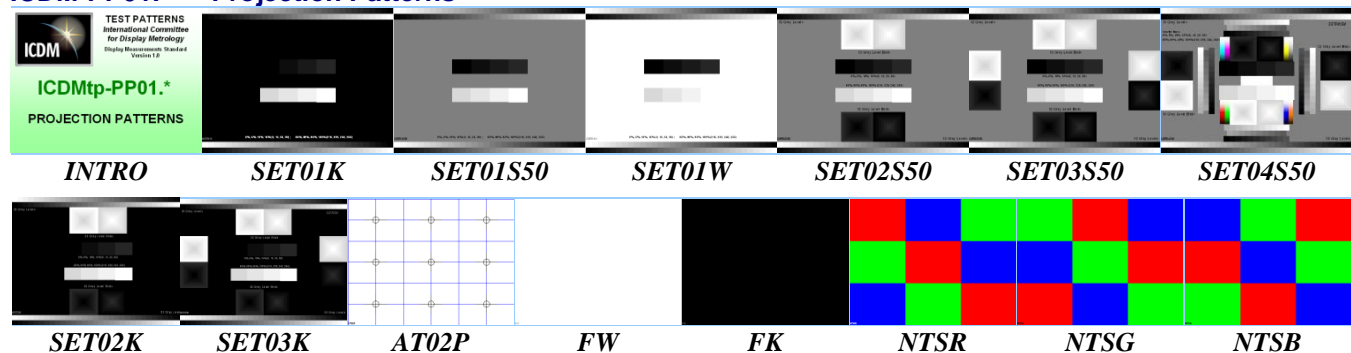
This pattern idea was originally developed for global-dimming displays. Measure the center box, use a frustum mask to avoid veiling glare in the detector. Not shown here are the similar primary-color renderings: CCPLR#, CCPLG#, CCPLB#.



ICDMtp-RP01.* — Reflection Patterns

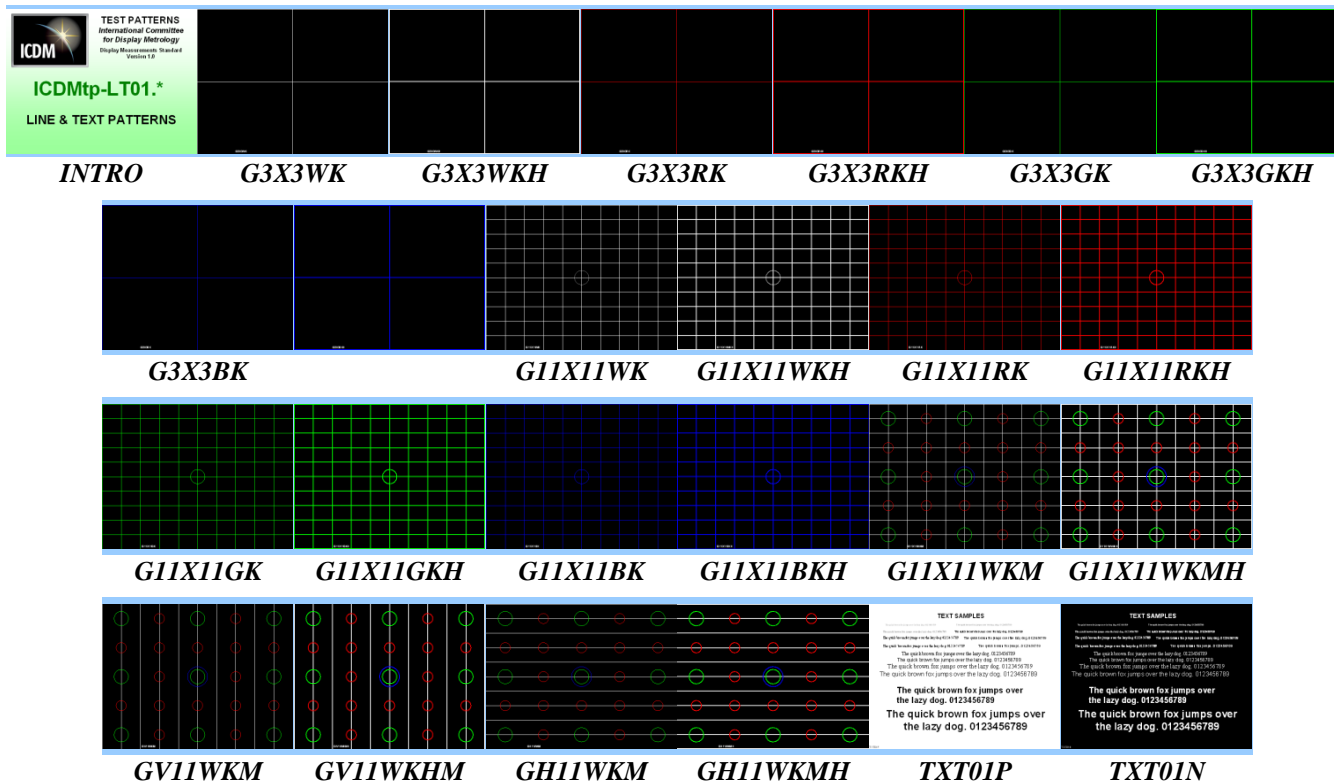


ICDM-PP01.* — Projection Patterns



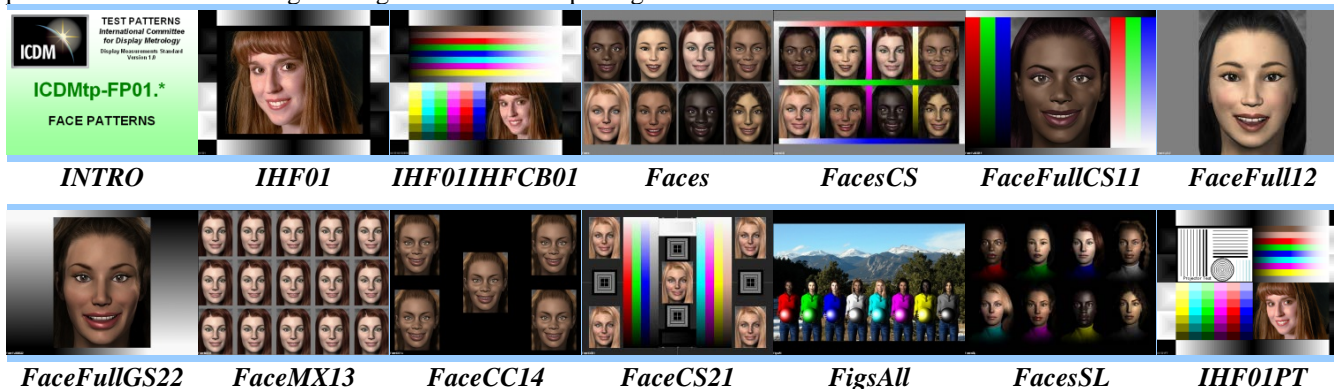


ICDM-LT01.* — Line & Text Patterns:



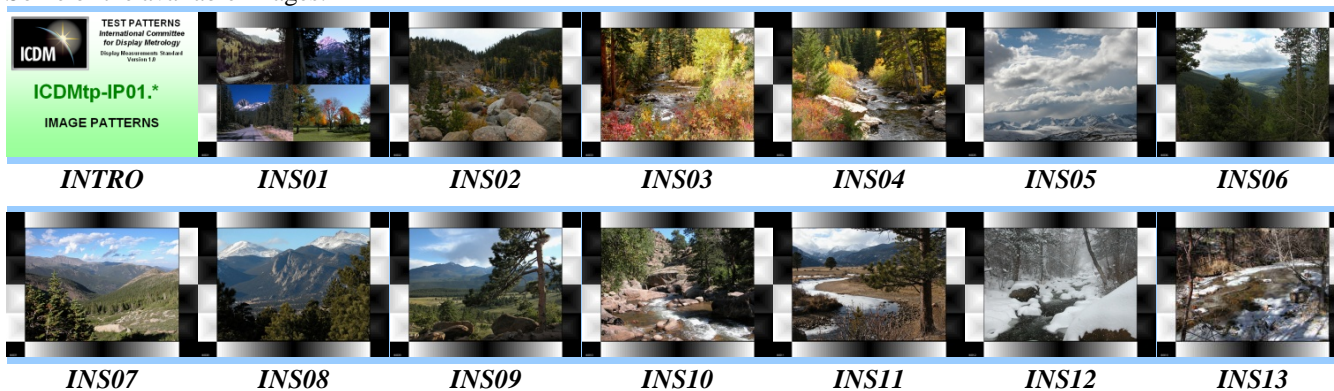
ICDM-FP01.* — Face Patterns

The content is limited to a few patterns to keep the file size reasonable. In the bit-mapped renderings there are more face patterns available including the originals for the computer generated faces.



ICDM-IP01.* — Image Patterns:

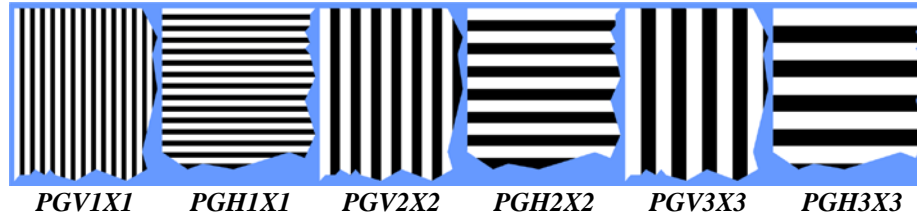
Some of the available images.



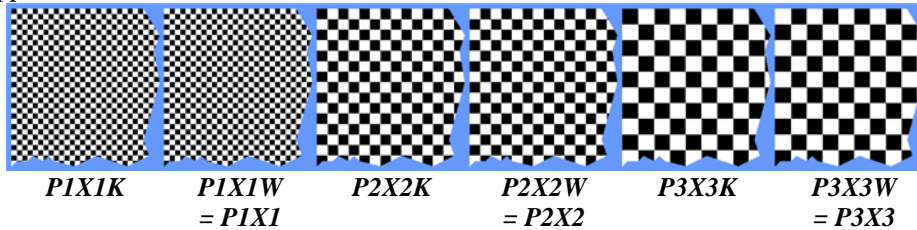


A12.3 BITMAPPED PATTERNS

A. Grilles (magnified for demonstration purposes). Unless specified otherwise, these will always start with white at left or top.



B. Pixel-based checkerboards (magnified for demonstration purposes). Unless specified otherwise, these will always start with white at the upper left corner.



C. Busy pattern (BUSY01): A busy pattern is designed to tax the display's capabilities in several ways. A variety of targets are used within—grilles, single and double-pixel checkerboards, diagonals, noise blocks, black and white blocks, and text samples. The largest blocks are 72 px square, and the smallest blocks are 36 px square. There are five gray levels used out of 256: 0, 63, 127, 191, 255 for 2×2 grilles and text samples. Noise blocks are single pixels randomly generated covering the range of 0 to 255 gray levels. See sample next page.

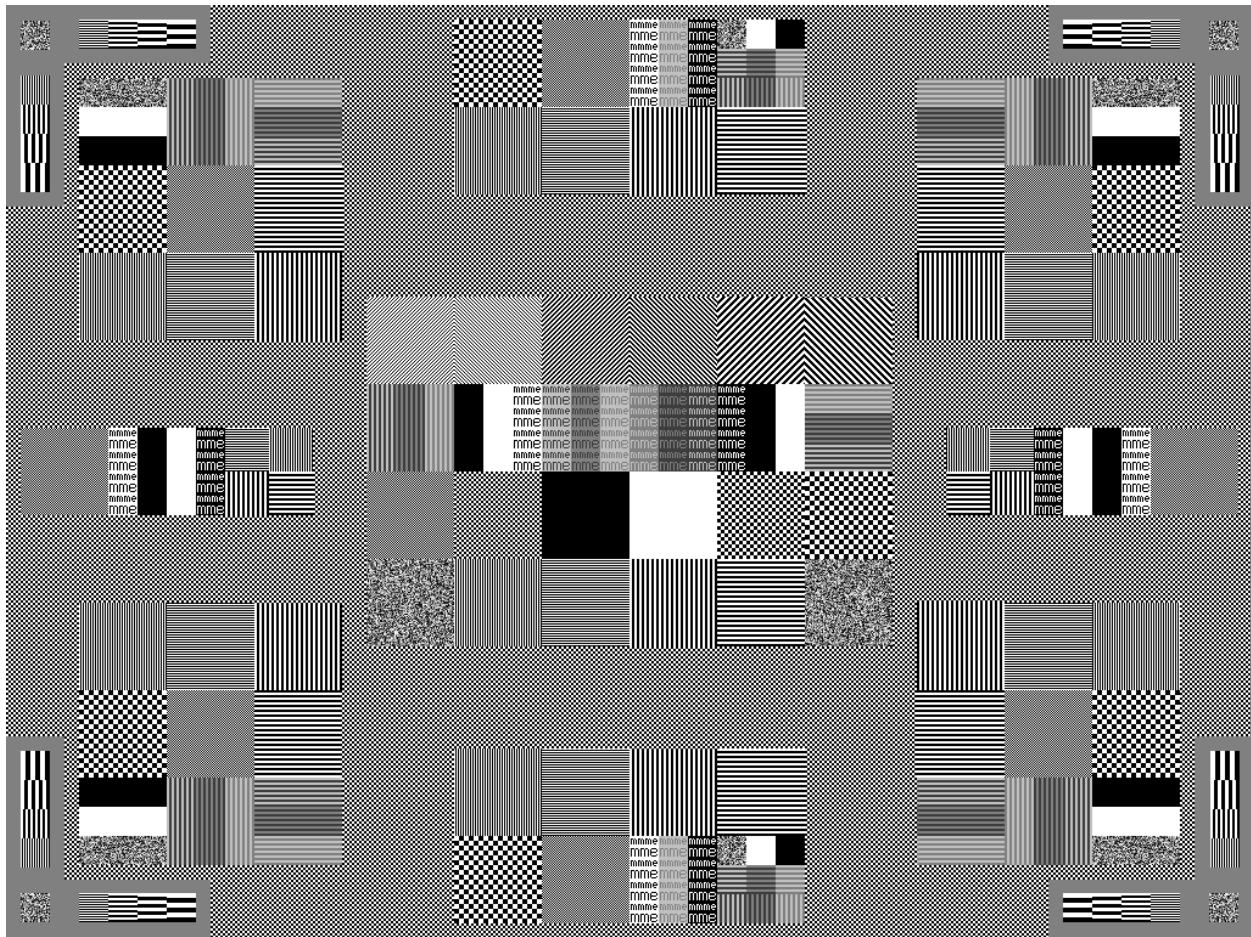
D. Centering and alignment target (CAT01): With a 60 px diameter round center black target. This pattern is useful when using detectors having a narrow measurement field angle in order to quickly find the center of the screen. See sample next page.

E. Highlight contrast pattern (HICON01): With a 30 px square center box of white on a black background. See sample next page.

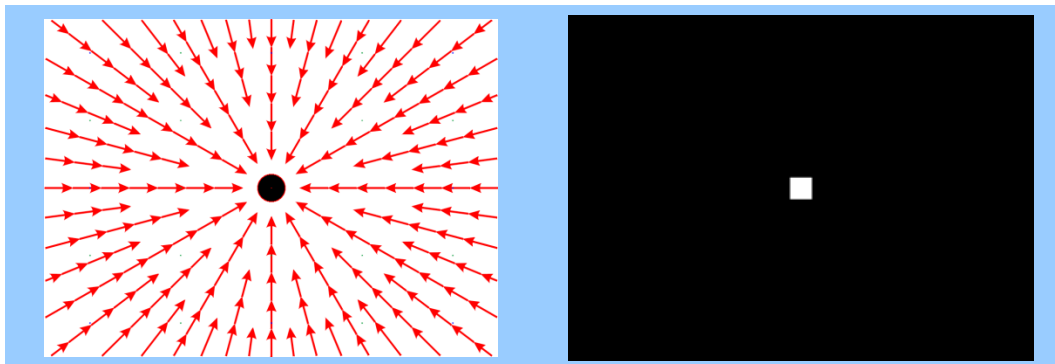
F. SMPTE-Based Pattern: We have included a bit-mapped pattern based upon SMPTE RP 133–1991 (see “SMPTE Recommended Practice: Specifications for Medical Diagnostic Imaging Test Pattern for Television Monitors and Hard-Copy Recording Cameras,” SMPTE Journal, pp. 580-582, July 1991—used with permission). This pattern must be a bit-mapped image. To the standard SMPTE pattern, we have added single pixel and double pixel checkerboards for black-and-white pixels and pixels at the levels of 53 % and 48 % (bit levels 135 and 122) as well as some text samples of varying contrasts. Two versions of this pattern are available for the appropriate screen pixel arrays (vsmpte133a_####x#### with only checkerboards added to the original SMPTE pattern, and vsmpte133b_####x#### with noise blocks and text samples added, where ####x#### = 640×480, 1024×768, 1280×1024, 1600×1200, etc.). See sample and construction details in the following pages.

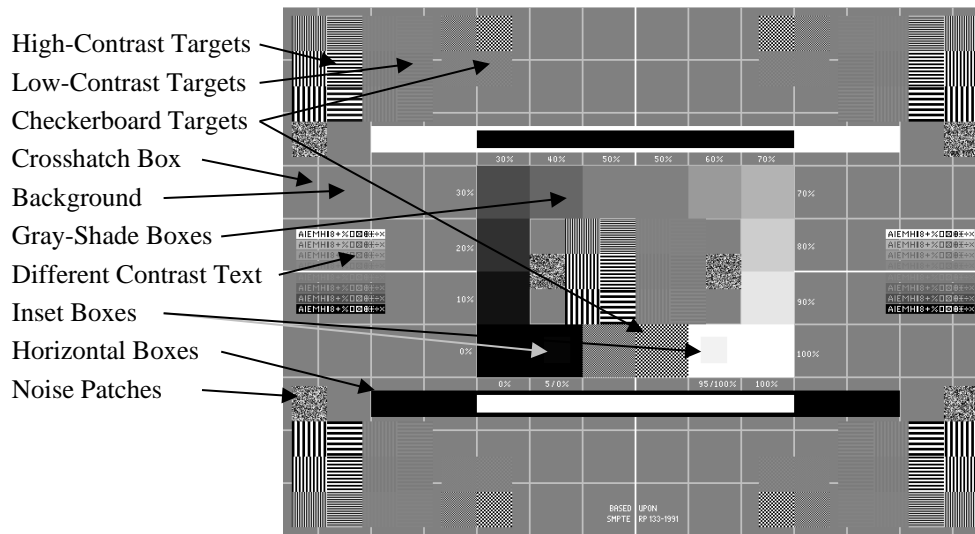


METROLOGY

*BUSY01*

METROLOGY

*CAT01**HICON01*



Geometry of Modified SMPTE RP 133 Pattern

Assumes horizontal screen with $N_H \geq N_V$: $B = \text{int}(N_V/10)$, $G = \text{int}(2B/3)$

HIGH CONTRAST GRILLE TARGETS Black & white vertical and horizontal: 1 x 1, 2 x 2, 3 x 3 px Placed $N_V/4$ from edge of pattern (top and bottom). Square, G .	LOW CONTRAST GRILLE TARGETS Gray levels on 2 x 2 px grid: Lowest contrast: 130, 127 (51%, 50%) Middle contrast: 130, 122 (51%, 48%) Highest contrast: 135, 122 (53%, 48%) Placed next to high contrast grill targets.
CHECKERBOARD TARGETS 1 x 1 px and 2 x 2 px both black & white and levels 135 & 122 (53%, 48%). Placed $N_V/4$ from grill targets.	DIFFERENT CONTRAST TEXT 122, 135 (48%, 53%) 102, 153 (40%, 60%) 76, 178 (30%, 70%)
CROSSHATCH BOX $N_V/10 \times N_V/10$ from center to center, $(N_V/10)-2$ interior size Lines: 2 px wide. Center lines H & V at white 255 (100%) Other lines at 191 (75%). Allow 1 px width at top and bottom.	NOISE PATCHES Same size as targets: $G/4$
HORIZONTAL BOXES Large (top white, bottom black): $B/2 = N_V/20$ high 10B wide. Small (top black, bottom white): $B/3 = N_V/30$ high 6B wide.	BACKGROUND 127 (50% level)
INSET BOXES 5% and 95% (13, 242) centered. Size: $B/2 = N_V/20$	
GRAY SHADE BOXES: Size: $B = N_V/10$. Edges placed at center of 2 px lines.	

Examples of Pixel Arrays for Modified SMPTE RP 133 Pattern

$B = \text{int}(N_V/10)$, $G = \text{int}(2*B/3)$, $B/3 = 2*\text{int}(B/6)$

N_H	N_V	$N_V/10$	B	Inset box		Grille Target G	Grille Borders $\text{int}(G/4)$	Horizontal Boxes				border $\text{int}(B/4)$
				$\text{int}(B/2)$	$\text{int}(B/3)$			Large 10B	$2\text{int}(B/4)$	Small* 6B	$\sim B/3$	
640	480	48	48	24	16	32	8	480	24	288	16	12
800	600	60	60	30	20	40	10	600	30	360	20	15
1024	768	76.8	76	38	25	50	12	760	38	456	24	19
1152	864	86.4	86	43	28	57	14	860	42	516	28	21
1280	1024	102.4	102	51	34	68	17	1020	50	612	34	25
1600	1200	120	120	60	40	80	20	1200	60	720	40	30



A12.4 COLOR & GRAY-SCALE INVERSION TARGET

The appearance of an image on an LCD can vary depending on the viewing angle. To evaluate the variation of luminance and color with viewing angle, we have developed a test pattern for easy detection of such variations. The name of the pattern is *CINV01*. The pattern, shown at the right, is a large-area test and a screen-uniformity test. For a large-area test, the largest circle encompasses the basic pattern; for a screen-uniformity test, that pattern is replicated (in reduced form) at nine locations including screen corners, edges and center. Because of the gray backgrounds, it can also be used as a quick check for gray-scale reversals, and hence augment the other measurement procedures.

Each major section of the large circle is a gray-level pie-wedge with a small circle inside it. The small circle contains red, green, and blue perturbations (R, G, B, arranged counterclockwise) on the gray wedge in which it is embedded. This counterclockwise ordering from R to G to B is a sort of spectral ordering and shows up as counterclockwise ordering in chromaticity space. When the colors reverse in one of the small circles, the areas labeled r, g, and b acquire chromaticities that are no longer counterclockwise in chromaticity space. The arrangement might be clockwise (e.g., $R \rightarrow C$ [cyan], $G \rightarrow M$ [magenta], and $B \rightarrow Y$ [yellow]).

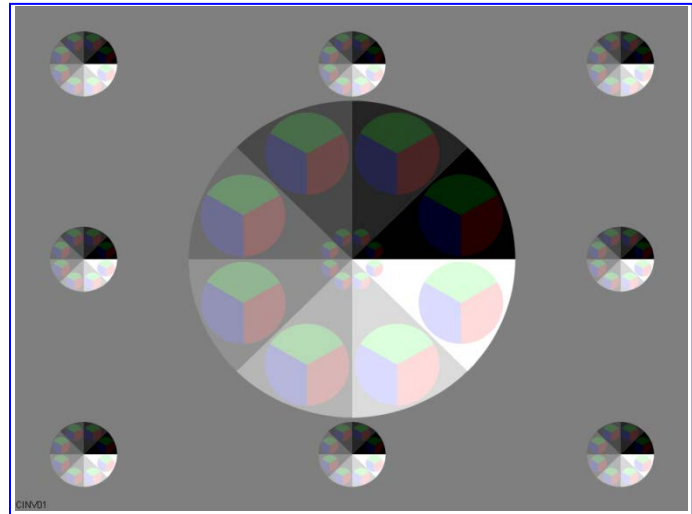
The theory behind the pattern is that the visual system forgives systematic changes in gray level and color but is highly sensitive to changes in gray-level and spectral ordering. When the ordering changes are extreme, it is as if we were suddenly confronted with a photographic negative instead of a positive. A single number quantifying the color reversal is readily obtained from clockwise-vs.-counterclockwise (CW-vs.-CCW) ordering of three labeled colors in chromaticity space. Standard color-blindness tests, such as the Farnsworth-Munsell hundred-hue test, reveal in normal individuals the visual system's ability to recognize and create such orderings; see M. H. Brill and H. Hemmendinger, "Illuminant dependence of object-color ordering," *Die Farbe* 32/33 (1985/6), p. 35.

The parameters of the pattern are as follows: A set of principal gray levels is chosen (the same ones used for eight-level gray-scale-inversion metrics). Denote the digital value for each gray level as the same number n in all three color channels (red = R, green = G, blue = B). For a given principal command level g_n (where $g_0 = 0$, $g_1 = 36$, $g_2 = 73$, $g_3 = 109$, $g_4 = 146$, $g_5 = 182$, $g_6 = 219$, $g_7 = 255$), measure three neighboring colors driven at the (R, G, B) digital levels as follows: reddish (g_{n+1} , g_n , g_n), at which we measure chromaticity (x_R , y_R); greenish (g_n , g_{n+1} , g_n) at which we measure chromaticity (x_G , y_G); and bluish (g_n , g_n , g_{n+1}), at which we measure chromaticity (x_B , y_B). For $g_7 = 255$, assign the same colors as for $g_6 = 219$. The approximate increment of 36 (out of a possible 256) is chosen so that the colors will in most cases be easily discriminable from each other. Small patches of these three colors are abutted so they all meet at a single point on the screen.

Upon looking at the pattern from varying viewing angles (typically the greatest sensitivity is in the vertical direction), several kinds of reversals may be seen:

1. Some of the gray levels may show decrease as one proceeds CCW around the large circle.
2. Some of the small circles may show a sudden reversal of spectral ordering. For example, the red, green, and blue may turn into their complements cyan, magenta, and yellow (again in CCW order). If this behavior occurs at the same viewing angle at which the embedded gray level participates in a gray-level reversal, the likely cause is that all three primaries undergo reversal at the same viewing angle.
3. Some of the small circles can show a fusion of the colors in their pie-wedges. For example, the red and green pie wedge can merge into a single yellow pie wedge that subtends 240 degrees. In that case, the ordering of the colored wedges cannot definitely be named as clockwise or counterclockwise in spectral order. However, there is still a pathology.

A general decrease in lightness or shift in color of the whole pattern may also be seen. This behavior can be regarded as pathology but is not so severe perceptually as one of the reversals listed above. If one does not see a reversal at any gray level or viewing angle, the display can be pronounced "reversal-free." Otherwise, viewing angles in various directions can be identified at which specific reversals take place.





A12.5 VISUAL EQUAL PROBABILITY OF DETECTION TARGET — EPD

The equal probability of detection (EPD) grayscale function assures each successive increase in input drive gray level produces an equal increase in perceived luminance (similar to DICOM, see § B25) except that the luminance steps among the darker gray levels are boosted slightly to enhance visual detection of dimmer low-contrast objects of interest residing among brighter surrounding areas in the image. Before performing any test that requires calibration, regardless of how the calibration was performed, it makes sense to have a quick visual check to ensure that the calibration is applied and to give a rough estimate of how good the calibration is. For this purpose, the Watson Visual EPD

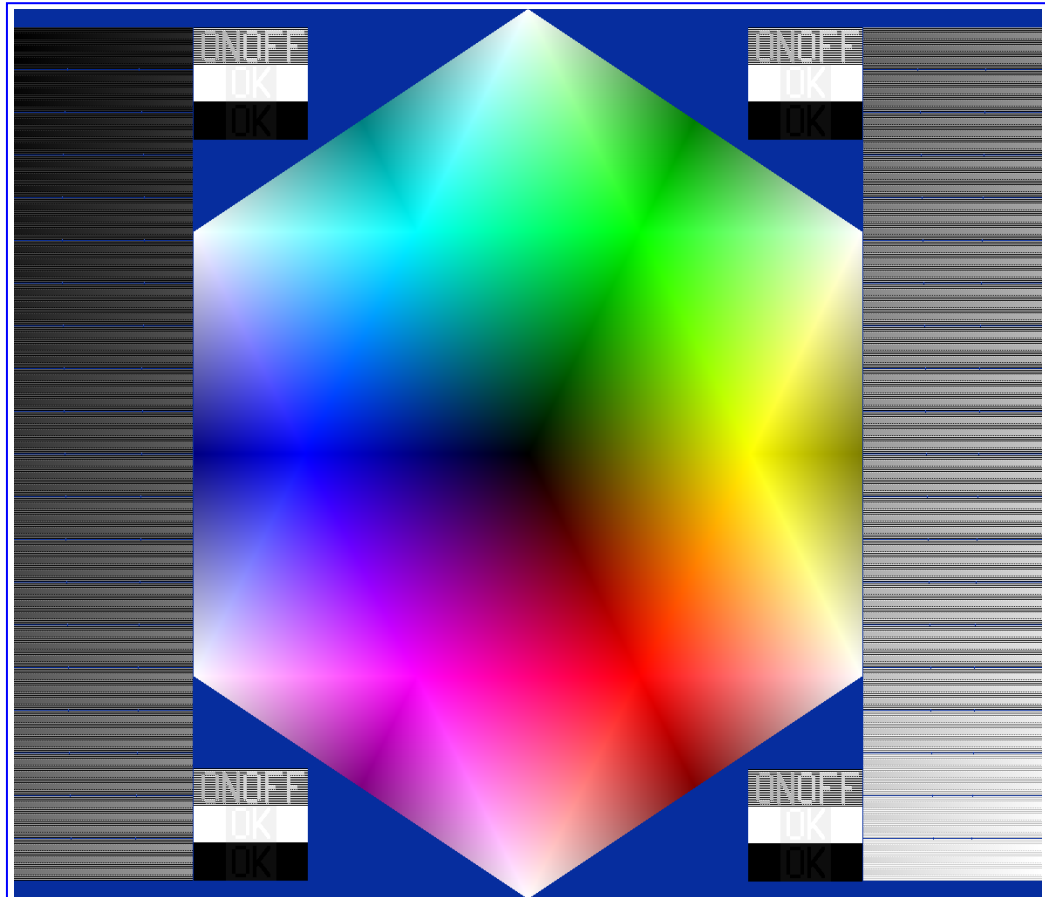


Fig. 1. Visual Equal Probability of Detection target (WatsonVEPD.bmp).

Target was created. It is a compilation of several quick-reference test patterns to evaluate the quality of an EPD calibration. This is a bit-mapped target designated as **WatsonVEPD.bmp** and is available at <https://doi.org/10.55410/igam8989>. There are three notable areas of the Watson Visual EPD Target test pattern:

1. Corner On-Off Squares: Four quick-check squares appear on the target that allow the user to evaluate if the monitor is calibrated to EPD (either "ON" or "OFF" become visible), experiences saturation in the white drive levels ("OK" appears in the white area when there is no saturation), or experiences black level cut-off ("OK" appears in the black area when there is no cut-off).

The ON/OFF calibration check is achieved by spatial dithering. Alternating one pixel wide black and white horizontal lines when viewed from a sufficient distance will blend into an average-luminance gray tone. The drive level that corresponds to that average luminance depends on the shape of the gamma curve. Using this idea, transitions between any two visibly different calibration states can be identified. For the Watson Visual EPD Target, "ON" blends into the background when the monitor gamma response is near a gamma of 2.2. "OFF" blends into the background when the monitor gamma response is near EPD. If there is a gamma shift with viewing angle, the ON/OFF calibration check will read differently for one or more of the four targets. Therefore, the placement of the four targets gives a crude assessment of the relationship between gamma response and viewing angle. This quick check will also give an indication of any vertical scaling produced by the combination of the monitor and graphics card (i.e. if the monitor is not running at its native resolution) as the spatial dithering will not work.

The white saturation check is made by drawing a light gray rectangle inside a white rectangle. The letters "OK" are written inside the light gray rectangle in white. The difference between the white and the light gray determines the smallest level of saturation you want to visually detect. (The Watson Visual EPD target uses drive level 255 for white and drive level 241 for light gray, but this can be varied to match any desired threshold value.) The black cut-off check is made the same way with a black and a dark gray rectangle. This time the letters "OK" are written in black. (The Watson Visual EPD Target uses drive level 0 for black and drive level 13 for dark gray.)



A12.6 Multicolor Pattern with Constant 25% APL

The concept in FIGURE A12.3 is to maintain the pre-gamma average pixel level (APL) at 25 % independent of what center color is being measured. Each of the nine large boxes have $2/9^{\text{th}}$ the width and height of the active display screen area. The corner sub-boxes have $1/18^{\text{th}}$ the width and $1/9^{\text{th}}$ the height of the screen. The boxes above and below center have horizontal sub-boxes that are $1/36^{\text{th}}$ of the screen height. The boxes on the left and right of center have vertical sub-boxes that are $1/36^{\text{th}}$ of screen width. The black border is $1/18^{\text{th}}$ of the screen height on the top and bottom and $1/18^{\text{th}}$ of the screen width left and right.

The only box that is measured is the center box. Most of the other surrounding boxes are held constant to sample the display gamut uniformly over the screen. There is a smaller grey box (in this example) that is intended to be the input digital complement of the code value of the center box color. For displays that are sensitive to APL loading effects, the small grey box is used to maintain the APL loading for different center colors. In the color example shown, the center box has an 8-bit RGB digital code value of (192,192,192), and the small gray box has the 8-bit complementary color (63,63,63). If the center box was changed to a mid-level cyan, such as (0,200,200), then the small box color would change to (255,55,55). If the display is not sensitive to APL loading, then this small gray box can remain a constant black color. In general, if the center color is (R, G, B) then the complement is (255-R, 255-G, 255-B) for a maximum level of 255. This pattern can be created following the rounding procedure described in A12.7 using an APL value of 24.7 %.

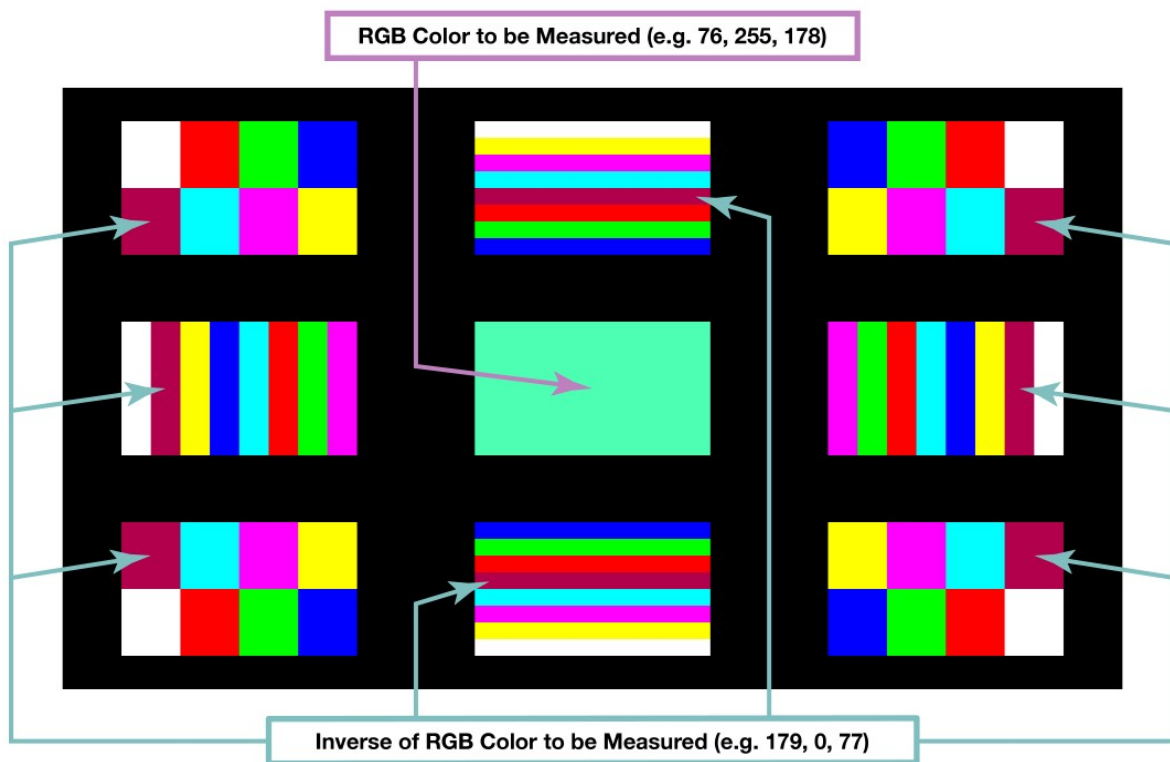


FIGURE A12.3. Concept of maintaining the pre-gamma average pixel level (APL) at 25 %.

A12.7 Selectable Constant Average Picture Level (SCAPL)

This appendix defines how to create a picture using a scalable pattern by aspect ratio that closely fits a selected APL (refer to the definitions section, below). By following the geometric design instructions, the pattern is repeatable by



different experimenters. Most common usage will measure the luminance and chromaticity of an arbitrary color in the center of the picture and with a selectable APL. A complementary loading pattern surrounds the center box containing a test color. By varying the complementary loading pattern based on the test color, the picture maintains a constant APL for any arbitrary test color. The colors use the [SMPTE EG 28-1993](#) definition for signaling defined by an (R', G', B') signal. Elements of the test pattern scale with both APL and the picture aspect ratio using nine equally sized boxes shown in FIGURE A12.4. The nine boxes have the same aspect ratio, which is approximately the same as the aspect ratio of the picture. The aspect ratios of the boxes differ only due to placement and size quantization. The eight surrounding boxes are further subdivided into equally sized small rectangles. Seven of these sub-rectangles are fixed color patches of white, red, green, blue, yellow, magenta, and cyan. The remaining $1/8^{\text{th}}$ rectangle in each surrounding box takes the complementary signal color of the test color. The total area of these eight complementary color rectangles sum to the area of the center box area in order to ensure a constant signal APL for any center color.

An example MATLAB[®] source code pattern designer will produce the pattern definition in this appendix and is available at [DOI:10.55410/jshq9099](https://doi.org/10.55410/jshq9099) for the user's convenience and pattern verification. The pattern designer can create pictures for later rendering or direct display rendering of the SCAPL pattern. In case images are built prior to an experiment, the user should employ lossless image storage in fully sampled three-component colors (4:4:4). This appendix makes use of the following terms and mathematical functions.

TABLE A12.1. Definitions of terms used in the SCAPL method.

Term	Definition
APL	Average picture-signal level in IEC Electropedia 723-05-75 shortened to average picture level or IEC 62977-2-1: 2021 referring to pre-gamma average picture level.
Achieved APL	The APL of the picture created by this pattern design as different from the input or desired APL.
Image signals	R', G', B' , see SMPTE EG 28-1993 .
<code>floor(x)</code>	The function returns a positive integer equal to the value of x with any fractional portion truncated.
<code>round(x)</code>	The function returns a positive integer equal to <code>floor(x)</code> if the fractional portion of x is less than 0.5, otherwise the function returns a value rounded up to the nearest positive integer.
test color	The color patch in the center of the test pattern created by the pattern design. See TABLE A12.3 and FIGURE A12.4 through FIGURE A12.7.

The SCAPL pattern design parameters refer to the figures in this section for their positioning within the display's active area. When referring to a specific color, this pattern design refers to the color in terms of its normalized floating-point value, between 0 and 1.0, inclusively. The pattern background is black when not obscured by a scaled box pattern. FIGURE A12.4 shows the non-black regions that scale uniformly by APL. The center box contains the color under test. Box A (FIGURE A12.5), Box B (FIGURE A12.6), and Box C (FIGURE A12.7). The original and flipped boxes align to center lines shown in FIGURE A12.3.



TABLE A12.2. Precise SCAPL pattern dimensions.

Symbol	Description	Derivation
V_{APL}	Average picture level (APL)	
h	Horizontal picture dimension (in pixels)	
v	Vertical picture dimension (in pixels)	
h_b	Horizontal dimension of Box A, B and C	$h_b = 8 \text{ round } \left(\frac{h}{8} \sqrt{\frac{V_{\text{APL}}}{5}} \right)$ or if $3h_b > h$ in the above formula, $h_b = 8 \text{ floor } \left(\frac{h}{8} \sqrt{\frac{V_{\text{APL}}}{5}} \right)$
v_b	Vertical dimension of Box A, B and C	$v_b = 8 \text{ round } \left(\frac{v}{8} \sqrt{\frac{V_{\text{APL}}}{5}} \right)$ or if $3v_b > v$ in the above formula, $v_b = 8 \text{ floor } \left(\frac{v}{8} \sqrt{\frac{V_{\text{APL}}}{5}} \right)$
d	Vertical dimension of a color stripe in Box B	$d = \frac{v_b}{8}$
w	Horizontal dimension of a color stripe in Box C	$w = \frac{h_b}{8}$

Note 1. The pattern design allows the experimenter to find the closest h_b and v_b that is divisible by eight to ensure that dimensions of color patches inside Boxes A, B and C are integers and proportional to the intended design.

Note 2. For both h_b and v_b , rounding to the nearest integer is optimal to build a picture as close as possible to the target APL but when the Target APL is large, usually $V_{\text{APL}} > 0.54$, the $\text{round}()$ function may set either h_b or v_b too wide. The routine tests to ensure three h_b widths and three v_b heights will fit in the dimensions of the picture.

Note 3. R', G', B' signals appear in a variety of references. This procedure refers to [SMPTE EG 28:1993](#) as a clear definition.

TABLE A12.3. SCAPL color assignments.

Color	Value
White	[1.0, 1.0, 1.0]
Black	[0, 0, 0]
Red	[1.0, 0, 0]
Green	[0, 1.0, 0]
Blue	[0, 0, 1.0]
Cyan	[0, 1.0, 1.0]
Magenta	[1.0, 0, 1.0]
Yellow	[1.0, 1.0, 0]
X (test color)	$[R', G', B']$
X' Complement of the Test Color	$[1 - R', 1 - G', 1 - B']$

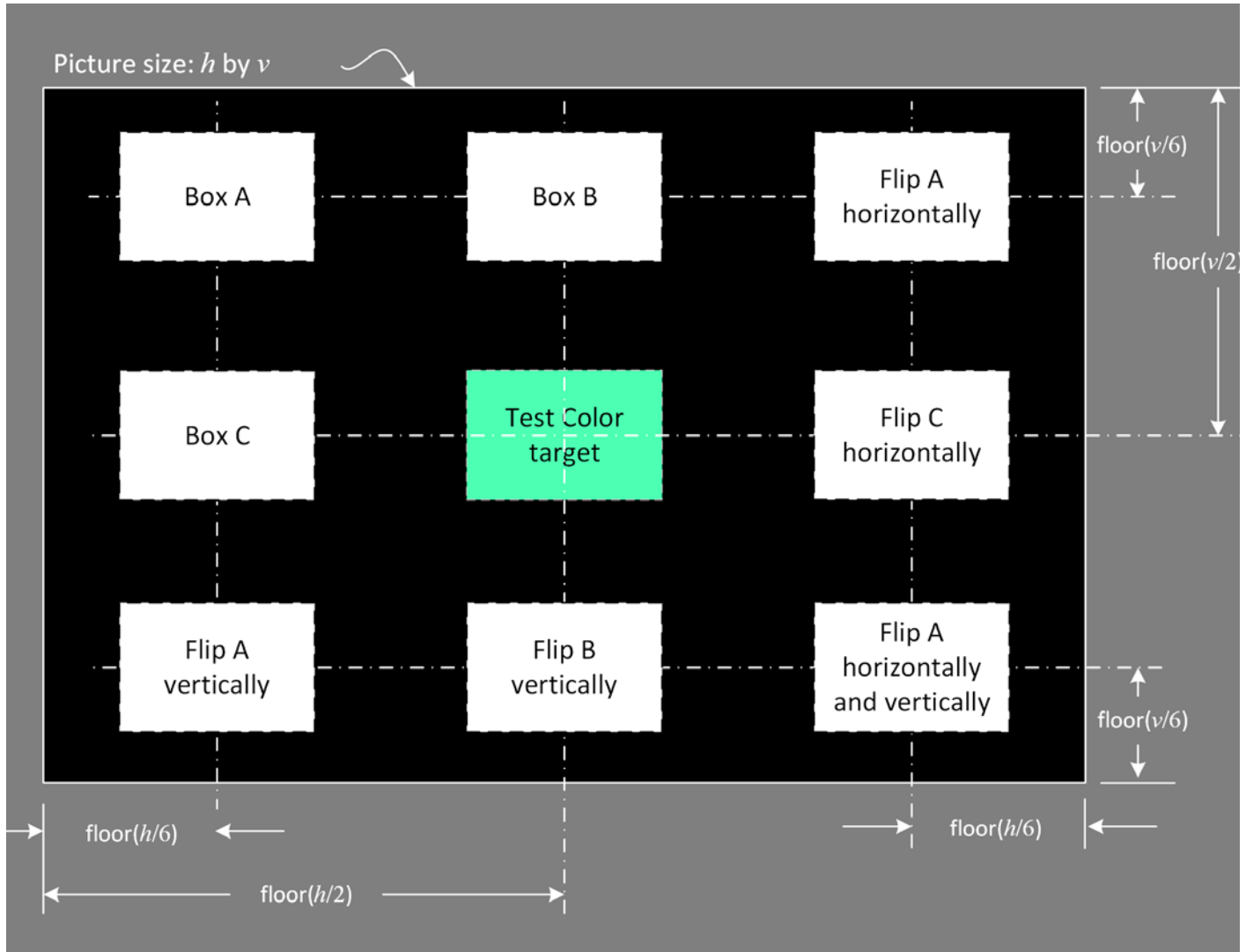


FIGURE A12.4. SCAPL pattern layout within a display's active area.

FIGURE A12.4 through FIGURE A12.7 show the same color under test, X , and color complement, X' , as is used in A12. Each inner box design positions either two or four orientations. For example, Box A as shown in FIGURE A12.5 fits into the top left box location in FIGURE A12.3. Next, perform a horizontal flip by reversing the picture elements horizontally. The operations using the MATLAB matrix manipulation function, `flip(matrix,dim)`, are:

A horizontal flip of a box is `flip(Box,2)`

A vertical flip of a box is `flip(Box,1)`

A horizontal flip followed by a vertical flip of a box is `flip(flip(Box,2),1)`

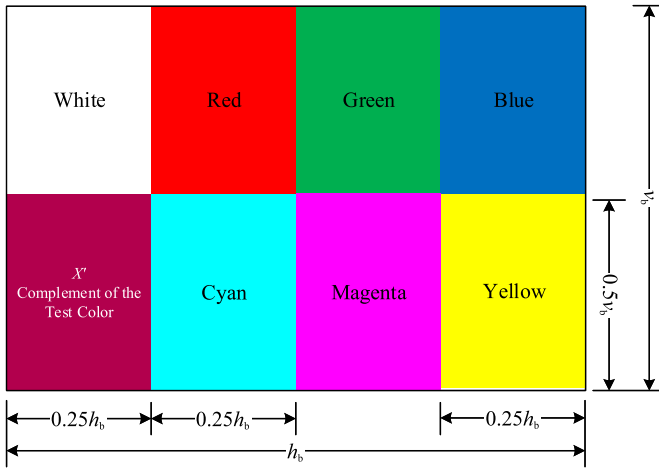


FIGURE A12.5. Interior layout of Box A.

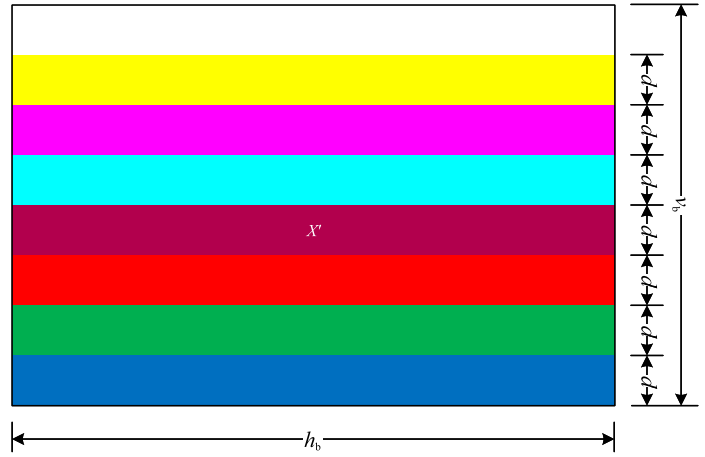


FIGURE A12.6. Interior layout of Box B.

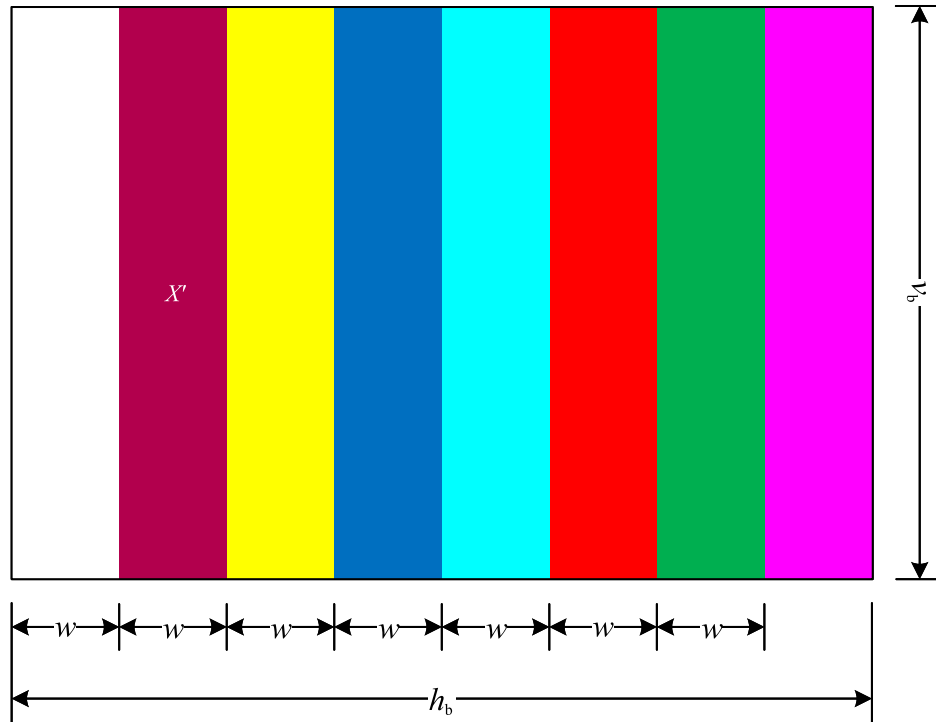


FIGURE A12.7. Interior layout of Box C.

The SCAPL pattern designer produced examples shown in FIGURE A12.8 with different APL and aspect ratios. Additionally, the pattern designer produced examples shown in FIGURE A12.9 with pictures increasing in APL but using a constant aspect ratio. The picture size used in the second example set is 1920×1080 . Below each example is the targeted APL and the achieved APL, $V_{\text{APL, achieved}}$. The achieved APL is often different by a small amount from the target APL, which users provide as an input to the SCAPL method. The following formula is used to compute the achieved APL of the examples.



$$V_{\text{APL, achieved}} = \frac{1}{3 \times n} \times \sum_{i=1}^n (R'_i + G'_i + B'_i), \quad (12.1)$$

where n is the number of pixels in the picture.

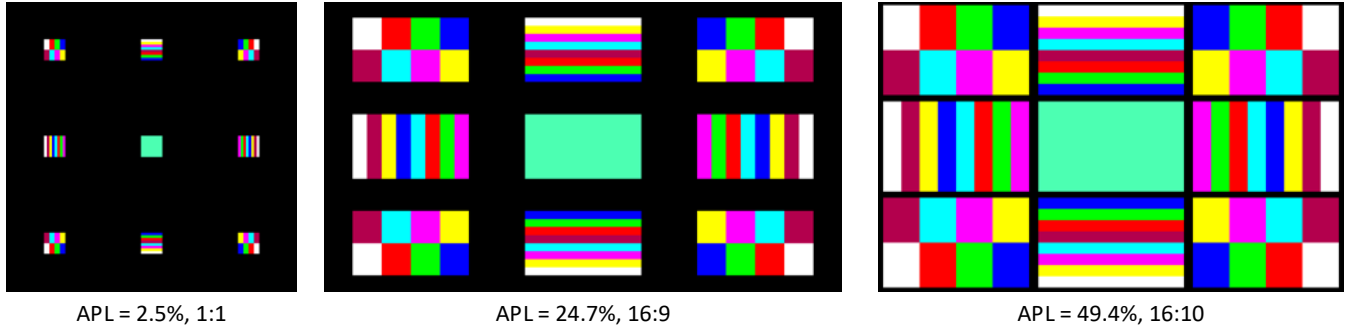


FIGURE A12.8. SCAPL examples showing different APLs and aspect ratios.

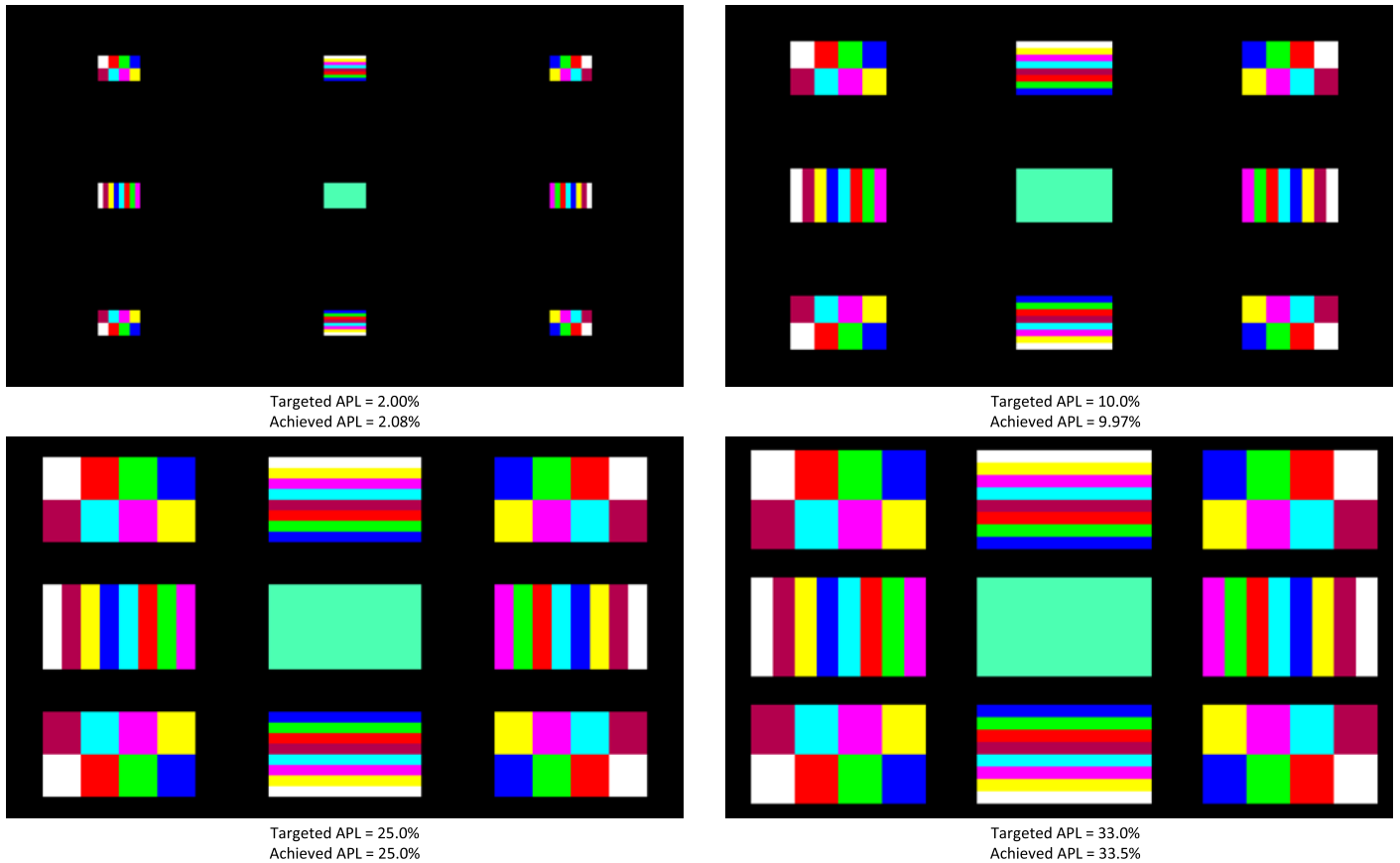


FIGURE A12.9. SCAPL 1920×1080 examples at a constant aspect ratio and increasing APLs.

The SCAPL has limits it cannot exceed. The boxes will grow uniformly until touching at an APL equal to 5 divided by 9, *i.e.*, 55.6%. The dimensional limit is self-evident since the center test box cannot exceed $1/9^{\text{th}}$ area of the picture, otherwise boxes will overlap. The $R'G'B'$ loading of the center box plus its complement distributed in the eight



Appendix A12 - Images and Patterns for Procedures

surround boxes yields an APL equal to $1/9$. The remaining portion of the surrounding boxes A, B and C without the test color complement adds an APL load equal to eight partial boxes times $1/18$. Thus, the maximum APL of a picture using this pattern design is equal to $1/9$ plus $4/9$ or $5/9$. The minimum APL depends on the active area's pixel count. The pattern designer code contains a lower limit following the guidance in Section 3.2.7, where the measurement area should contain at least 500 pixels.

Without the rounding treatment used by the equations in TABLE A12.2, the floating-point operations would yield non-integer results. In order to conveniently map the dimensions to integral pixel locations, the pattern design introduced a rounding function for h_b and v_b with a guaranteed factor of eight. The factoring ensures the boxes' interior dimensions, d and w , are integers. The recommended arithmetic forces SCAPL to be quantized in a particular way. Therefore, a procedure using this pattern should mandate reporting the achieved percentage APL in order to convey an accurate characterization of a test, using three significant digits.



A13 AUXILIARY LABORATORY EQUIPMENT

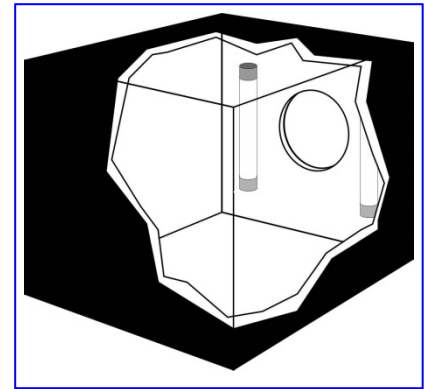
In addition to the LMDs used to perform the colorimetric measurements in this document and any signal generation equipment, oscilloscopes, and other electronics, there are several other objects and instruments which are mentioned and are found to be useful.

A13.1 UNIFORM LIGHT SOURCES

Integrating Sphere Light Source: An integrating sphere light source can be useful in several ways: (1) It can provide a source of calibrated luminance provided, of course, that it has been properly calibrated. (2) It can provide a source of luminance which is uniform over the exit port. Conventional wisdom suggests an exit port diameter of 1/3 the sphere diameter or less will provide a $\pm 1\%$ to $\pm 2\%$ nonuniformity of luminance across the exit port if the interior of the integrating sphere is covered with a diffuse white reflectance material having a 96 % reflectance or greater. This source is very handy for many diagnostics. If you are focusing on the source, always focus on the exit port of the integrating sphere. If it is well designed, its stability over long periods of time can be impressive, and its uniformity can hardly be replicated with other sources. A real pleasure to use.

Polystyrene Box Source: Virgin, white, closed-cell, polystyrene-foam boxes (for keeping food or medical items cold in shipping) can be used to make a relatively uniform large-diameter source (150 mm diameter), much the same way we'd make a box source below. Some have used picnic coolers to create sources and relatively uniform ambient illumination environments.

Box Source: A large box (cube) with its interior painted with the brightest matte white paint available in a hardware store can be used for a large-diameter source. Alternatively, a large polystyrene box may be used without having to paint the interior surfaces. The exterior is usually painted matte black. A hole is cut in the center of one face and a large fluorescent circular light is placed behind the hole or two short straight fluorescent lights are placed on each side of the hole. Unless the fluorescent light is powered with high-frequency ac (as are many LCD backlights), there may be a power-frequency oscillation that can affect short measurements. Similarly, properly baffled tungsten-halogen bulbs may also be used with dc power. The bulbs can be placed in each interior corner of the face with the hole. The bulbs should be mounted away from the painted surface since they get rather hot. Place a rectangular white flat baffle (made of polystyrene foam, for example) in front of the lamp so that the lamp doesn't directly illuminate the interior face of the box opposite the hole. Be careful not to place the baffles too close to the hot bulbs. Be sure to provide ventilation holes below any bulbs near the bottom and especially over the bulbs at the top.



A13.1.1 RONCHI RULING:

A Ronchi ruling is a glass substrate with black opaque (or chrome) lines of width equal to the line spacing between black lines. They are used to: (1) test for adequacy of spatially resolved high-contrast luminance measurement capability, and (2) provide spatial calibration of an array photodetector.

A13.1.2 NEUTRAL DENSITY FILTERS:

Neutral-density filters (NDFs) are used to decrease high-intensity light from overdriving or saturating the LMD and to extend LMD measurement integration time to avoid temporal aliasing with a refreshed display. There are generally two types. One is made of semi-transparent glass, and the other is made from evaporated metals. The deposited metal types tend to modify the spectrum of the transmitted light to a much lesser degree than some of the semi-transparent glass materials, however they sometimes have small pinholes or can be scratched if they are not coated with a protective coating. Keep the spectral modification in mind if either accurate photometric or colorimetric measurements are to be made for the density of the filter can change with the spectrum of the illumination. The transmittance $T = L_{\text{NDF}}/L_0$ is related to the density D by: $T = 10^{-D}$, $D = \log T \equiv \log_{10} T$.

A13.1.3 REFLECTANCE STANDARD:

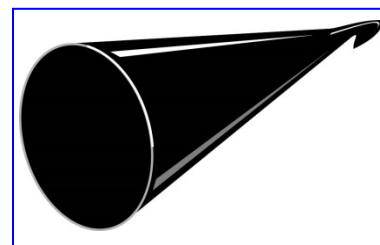
Diffuse white reflectance standard samples can be obtained with diffuse reflectance of 98 % or more. Some materials can be carefully sanded (some require water with the sanding) or cleaned to refresh the surface back up to its maximum reflectance should the surface become soiled or contaminated. Such reflectance standards can be used for making illuminance from a luminance measurement of the standard ($E = \pi L_{\text{std}} / \beta_{\text{std}}$) only for the measurement geometry used to determine its luminance factor β —the geometry used to calibrate the standard. If the reflectance (or diffuse hemispherical reflectance) is associated



with the standard—as the number of 98 % or 99 % usually does refer to the reflectance—then that value can only be used for a uniform hemispherical illumination. If we use an isolated source at some angle, there is no reason to expect that the 99 % value is even close to the proper value of the luminance factor for that geometrical configuration. Such standards must be opaque when used in front of a source of light such as an emissive display. Sometimes we can use a thin white card as a substitute when we need a thin material, but the card must be opaque, and it must be specifically calibrated for the source-detector geometry for which it is being used—such paper cards are not Lambertian either.

A13.1.4 CONE LIGHT TRAP:

These can be made from thin black gloss plastic. They can be used to provide a source of deep black for determining the zero offset of any instrument. Round cones are best (shown), but square cones are also useful. For the best performance it is helpful that there not be a dimple at the apex to reflect light. With plastic it is possible to squeeze the apex flat and bend it around upon itself to avoid the dimple.



A13.1.5 GLOSS BLACK PLASTIC:

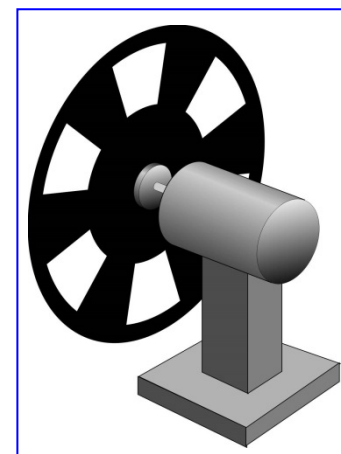
Gloss-black plastic is used to make cone masks, flat masks, replica masks, light traps. These items are useful in diagnosing glare and other problems in the optical system. Such black targets serve as reference blacks provided; they are not reflecting illuminated areas in the room into the LMD. These can also be used to cover reflecting surfaces. Vinyl plastic having a thickness of 0.25 mm (0.010 in) is easily shaped, bent, and cut with scissors or a knife. Vinyl plastics having a thickness of 0.75 mm (0.030 in) are stiff and best for making flat surfaces that you don't want to bend easily. Check local listings for plastic suppliers to obtain sheets.

A13.1.6 MATTE BLACK PLASTIC:

Matte-black plastic is used in making masks and black targets to diagnose glare or other problems where a gloss black target is impractical or would reflect too much light into the lens, for example, when the lens is very close to the target. These can also be used to cover reflecting surfaces. Vinyl plastic having a thickness of 0.25 mm (0.010 in) is easily shaped, bent, and cut with scissors or a knife. Vinyl plastics having a thickness of 0.75 mm (0.030 in) are stiff and best for making flat surfaces that you don't want to bend. Check local listings for plastic suppliers to obtain sheets.

A13.1.7 CHOPPER :

A chopper is useful in running diagnostics on temporal response measurements of light detectors used in conjunction with a stable laser. Additionally, a clear plastic disc can also be mounted instead of the chopping disc for reducing the coherence of a laser beam (to reduce the speckle in the reflected light, for example). Spray the disk with a workable fixative available in an art supply store heavier on the outer diameter (hairspray might work as well). Pass the laser beam through the spinning disk at a radius that provides the least speckle in the reflected light distribution but retains a narrow enough beam to be useful. Choppers are available through optical supply companies. Note that this is not a shutter as would be used in a single-shot camera; a chopper and a shutter are different things.



A13.1.8 POLARIZERS:

These are helpful in making diagnostics on the light detector's sensitivity to polarization. Several types are available from polarizing plastic sheet films to polarizer filters used with common cameras to high-quality prism polarizers. For most of the purposes of this document the inexpensive kind available at a camera shop will be adequate for diagnostics. If you get the plastic film type, be sure that they are not significantly colored like amber or brown. These are available from optical supply companies or camera stores. Circular polarizers can be used to de-polarize a laser beam with some success.

A13.1.9 LASERS:

The simple and readily available He-Ne red laser (632.8 nm) is a useful tool for aligning optical systems and devices and for diagnosing the temporal response of the light detector that is used in conjunction with a chopper. If the laser is to be used for light measurements in some way (e.g., BRDF measurements or temporal response measurements) it should be a stable laser, and these are considerably more costly than unstabilized lasers (BRDF measurement may require unpolarized light and a way to make the beam incoherent). The inexpensive He-Ne lasers are not usually very stable. Attention should also be paid to the



polarization state of the laser beam if the laser will be used for measurements. It is best to get the randomly polarized lasers to avoid problems of polarization. The unpolarized laser beam can be polarized using an inexpensive polarizer from a camera shop. These are available through optical supply companies. Laser pointers can also be used for alignment purposes.

A13.1.10 LED & PULSE GENERATOR:

A fast LED and a fast pulse generator that can create pulses with fast risetimes can be used to generate light pulses with fast risetimes to test the temporal response of an LMD like a photodiode or photomultiplier. LEDs are obtainable in a variety of colors but be sure that the LED used is fast—high-speed LEDs are available with risetimes of 10 ns or less. The speed of the LED depends upon the display technology. Pulse generators are available through electronics suppliers and equipment manufacturers. LEDs are commonly available from electronics parts suppliers.

A13.1.11 BLACK FELT:

Black felt is a fabric that is usually blacker than most other flat-black paints and materials. It has a tendency to shed its fibers, however, so care must be exercised when using it around surfaces that need to be clean. This is available through optical supply companies or fabric companies.

A13.1.12 FLOCKED BLACK PAPER:

Flocked black paper is blacker than most flat-black paints, but not as black as black felt. It has a surface that is somewhat like a fine-grained velvet. This is available through optical supply companies. Sometimes you want to put a black metal or plastic tube around the entrance of some optical configuration to restrict stray light from the surround. Putting flocked black paper on the inside of the tube can help further control the stray light.

A13.1.13 BLACK TAPE:

There are a variety of black tapes to use. Whatever you chose, it is wise to know the spectrum over which it is black. Some black tapes will transmit or reflect well in the IR. For example, it may be better to use the black masking tape rather than black electrician's tape because electrician's tape may be semitransparent to IR. Optical supply companies or art supply stores offer black masking tape. The quality of the tapes varies. Some are black both sides and some are not very black on the sticky side of the tape. Try to get the tape that is black on the sticky side if you use the masking type of tape. Also, be wary of leaving some kinds of masking tape on an object for a long period of time, some tapes can leave a mess if you try to remove them. Black duct tape can be difficult to remove cleanly.

A13.1.14 RESOLUTION TARGET:

NIST 1010a and Air Force resolution targets can be useful for examining the effects of veiling glare for high-magnification optical systems and for determining the magnification of an imaging system (number of detector pixels per millimeter of the image). These are available through optical supply companies.

A13.1.15 BLACK GLASS

Black glass (e.g., RG-1000) or a very high neutral density absorption filter (density of 4 or larger) can be used to measure the luminance of a source provided that the specular reflection properties are properly measured. Such a reflector acts much like a front surface mirror that has a low specular reflectance of usually between 4 % and 5 %. These can be helpful when you can only see the source using a mirror, or when you want to measure the luminance at the same order of magnitude of a reflection measurement rather than measuring the source directly. Note that how you clean the surface and the specular angle that is used will affect the value of the specular reflectance, so it must be calibrated for each configuration to obtain the best results. Also, because the glass can be corrupted by pollutants in the atmosphere, routine calibration is required as well.



A14 HARSH ENVIRONMENT TESTING

For testing of the display outside the default ranges of humidity, temperature, and pressure accommodated in this document it is left up to the user to determine if their measurement equipment is suitable for the harsh environments of interest. This section outlines some of the difficulties that may be anticipated in making these measurements. There are several configurations of the measurement equipment and the display that will be discussed. Goniometric measurements can be performed by moving the measurement equipment or moving the display. Usually, there is a chamber that provides the desired environment for testing the display. Probably the easiest way to see if the chamber has any effect on the measurements is to measure the display in a properly darkened room without the chamber, then re-measure the display in the chamber under similar conditions of temperature, humidity, and pressure as found in the room. Problems with reflections or measurements through any glass will be indicated and presumably correction may be made to the readings. This assumes that the display doesn't change its characteristics dramatically when under harsh environments; should the display change greatly, then the corrections obtained with and without the chamber may not be entirely appropriate. Here is where direct testing and characterization of the measurement system with and without the chamber would be required.

Should it be found that the reflections from the interior walls or glass window affect the measured results, steps can be taken to reduce the reflections. The user may wish to either coat the interior surfaces with a flat black paint (if this won't affect the performance of the environmental chamber) or hang black felt on the interior surfaces. The black felt is appealing since it is usually darker than flat black paint and it can be removed. These precautions may reduce the amount of reflections so they don't affect the measurements.

ALL DEVICES IN THE CHAMBER:

Both the measuring equipment and the display can be in an environmental chamber. In this situation, the measuring equipment needs to be able to perform within proper specifications for the range of environments that will be explored. If the measurement equipment changes its performance with a change in environments, then corrections must be made to the measurements accordingly. If the manufacturer doesn't supply such corrections (if needed), then the user will need to obtain them via experimentation and testing. An integrating-sphere light source and suitable paints may be useful for such testing, though the temperature may affect the performance of such sources. Glass filters must be used with caution since their transmission characteristics are usually sensitive to the absolute temperature. Fiber optic sources may be suitable for testing provided their transmission characteristics are either unaffected by or can be corrected for different temperatures.

MEASUREMENT EQUIPMENT OUTSIDE THE CHAMBER:

If measurements are made by equipment outside the chamber, then there must be a window through which measurements will be made. Again, the best way to see how much the window affects the measurements is to make the same measurements on the display with and without the chamber (set at the same environment as the room). Likely there will be a reduction of luminance because of the glass reflecting light back into the chamber, so a correction will be needed. There is also a possible effect from the polarization of the emitted light from the display interacting with the window differently than unpolarized light. A polarizer and a uniform light source can be used to diagnose polarization-induced luminance errors at various angles through the window (see Polarization Effects Diagnostics in this section for more information).

DISPLAY AND GONIOMETER IN CHAMBER:

The measuring equipment is outside the chamber, but the display and the goniometer are placed inside the chamber so that the display is rotated. If the display is rotated in the horizontal plane (about the vertical axis), there is generally no change in the display performance; but when the display is rotated in the vertical plane, the user must be sure that the display doesn't change its characteristics because of the change in direction of gravity relative to the display. Under extremes of temperature and under vacuum operation care should be exercised that the positioning equipment (goniometer) is suitable for that task.

DISPLAY IN CHAMBER:

The display can be in an environmental chamber and the measuring equipment capable of making goniometric measurements are outside the chamber. For measurements made through the glass at an angle, there may be polarization effects encountered and reflection complications. By comparing measurements made with and without the chamber at the same conditions of humidity, temperature, and pressure, corrections should be able to be made for any anomalies.

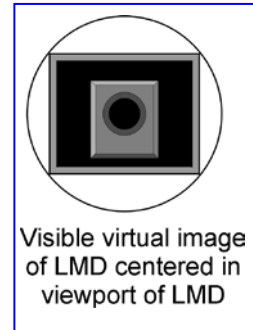


A15 ESTABLISHMENT OF PERPENDICULAR

There are various methods to establish the normal (perpendicular) of the surface of the center screen. Good alignment is essential in order to compare results between laboratories. Many discrepancies arise because of bad alignment and poor identification of the display normal.

A15.1 DISPLAYS WITH SPECULAR REFLECTION

Some display surfaces have a regular specular component of reflection (mirror-like producing a distinct image). When this is the case, the image of the lens of the LMD can be seen in the surface of a black screen. If the reflection of the lens is difficult to see, you can put a polystyrene foam cup with its bottom cut out over the lens to make the lens more visible in the reflection. Be sure to focus on the image of the LMD and not the screen surface (for this setup only, generally we always focus on the screen). Alignments within better than 0.1° with the perpendicular of the screen are readily possible this way. The alignment of a screen with a specular surface may also be obtained using a laser or laser pointer that is aligned with the center of the measuring instrument—see A15.4 below.



A15.2 MIRROR OR GLASS HELD ON SURFACE OF DISPLAYS

DANGER: *This method touches the screen. Be sure that the screen is capable of such rough handling before touching the surface.* If the display doesn't have a specular component of reflection, we can attempt to supply one using the following methods: A thin mirror or thin piece of glass placed against the face of the DUT will permit you to view the lens of the LMD in the display surface and adjust the rotation of the display until the image of the lens is centered in the viewfinder. Be careful not to damage the surface of the display in either holding the mirror against the surface or attaching it temporarily to the surface of the display. Some display surfaces are slightly flexible, and a mirror will deform the surface making this method unsuitable if the mirror is pressed against the surface with a holder or your fingers. Some place a thin mirror (0.7 mm thickness) on a stick and carefully position it gently against the screen surface. Others attach two threads to the mirror and hang the mirror from the display bezel to gently touch the display surface being careful that the mirror is flat against that surface. Some use double-stick removable tape on the back of the mirror to attach a very thin mirror or piece of glass to the display surface (the reason for the thin mirror is that it may avoid distorting a flexible surface). When the mirror or glass is in place, we align the display using the above A15.1 Displays with Specular Reflection.



A15.3 MECHANICAL ALIGNMENT

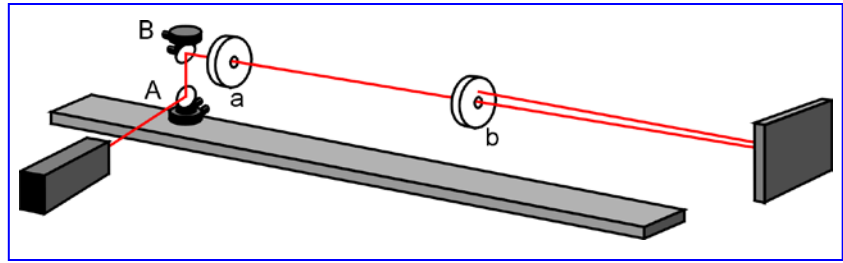
DANGER: *This method might touch the screen. Be sure that the screen is capable of such rough handling before touching the surface.* Here you use a good level to assure that the screen is vertical and that the optical bench is horizontal. If the screen will permit a level to touch its surface (and be otherwise handled) then you can place the level directly on the surface of the screen. If you can't touch the screen, you might be able to trust that the surface of any surrounding bezel is parallel with the surface of the screen, but that's a risky assumption. If the LMD is also level, then getting within 0.3° should be possible if you are careful. The problem here is that you only get alignment in the vertical direction with the level. The horizontal distance from the left and right side of the screen must be measured carefully to a point on the center of the optical rail or bench defining the axis of the measurement system. This is probably the least accurate method and should be verified by the other methods contained herein.





A15.4 ALIGNMENT WITH OPTICAL RAIL

If the LMD is on an optical rail that points toward the display, it may be important that the rail is perpendicular to the surface of the screen. Thus, the LMD can be moved back and forth along the rail without changing the position of the observation spot on the display. Such an alignment can be accomplished using a laser beam. An inexpensive He-Ne laser will do. Using a



beam steering device, mirrors A & B (available from optics suppliers, mounting not shown), make the laser beam at the desired height of the LMD lens position. Make two targets with a small hole in their centers. Each target can be placed within a ring (not shown) mounted on a carriage (for the rail, not shown) and its position adjusted with screws. The position of the laser beam nearest the beam steering device (B) should be at the height of the target. Move the target (a) near the beam steering device and adjust the mirror nearest the laser (A) so that the laser beam goes through the hole in the first target (a). Adjust the second mirror (B) so that the beam goes through the second target (b). This can also be accomplished using one target. When the target is near the beam steering device adjust the mirror furthest from the target or nearest the laser (A). When the target is down the rail away from the beam steering device, adjust the mirror closest to the target or furthest from the laser (B). By going back and forth, the adjustment will converge on the laser beam being exactly at the level of the hole in the target and exactly parallel to the rail. This laser beam can now serve as a pointer to the center of the screen. The reflected laser beam, if there is a specular component of reflection, will now reflect back toward the rail. With the laser beam going through the target placed at the end of the rail nearest the display, the reflected beam will hit the front of the target (facing the display) as the display's normal approaches the direction of the laser beam. When the laser beam folds back on itself, then the display surface is exactly perpendicular to the rail (the laser beam is shown in the figure to fold back a little high above the hole for illustration purposes). The LMD can now be adjusted so that it looks parallel to the rail. Use a targets at close focus and at the end of the rail. Adjust the position and rotation of the LMD until the target can be moved up and down the rail and the LMD always focuses at the center of the target.

A15.5 RUGGED DISPLAYS WITHOUT SPECULAR REFLECTIONS

DANGER: This method touches the screen with objects and perhaps liquids. Be sure that the screen is capable of such rough handling before touching the surface. Displays that don't exhibit a regular (mirror-like producing a distinct image) specular reflection yet are rugged enough to permit touching the surface might be temporarily modified to permit optical alignment. An alternative to using a mirror is to use a glossy plastic wrap material available in grocery stores. Such plastic may stick to the surface of the display sufficiently and threaten it the least. The reflection of the LMD lens may be observable by means of the gloss-plastic covering. You can place a small white target in front of the center of the lens or put a white shroud around the lens if it is difficult to see. If the surface is very rugged and can be washed with water, you can try some hair gel or glycerin between the clear plastic and the surface of the screen. Then smooth the surface with a flexible and soft squeegee (the free end of a pad of paper might work—without the cardboard). If that rugged surface of the screen is not very flexible, then a microscope slide or a cover glass might also be used with the gel to define a distinct-image specular surface. The gel or liquid used can be removed with water. When cleaning, use distilled water if possible and a soft cloth (suitable for cleaning optical surfaces) or lens tissues. Paper towels, facial tissues, etc., can put small scratches in the surface of the screen—be careful. Again, use these methods only if the surface of the display is designed for such rough treatment.

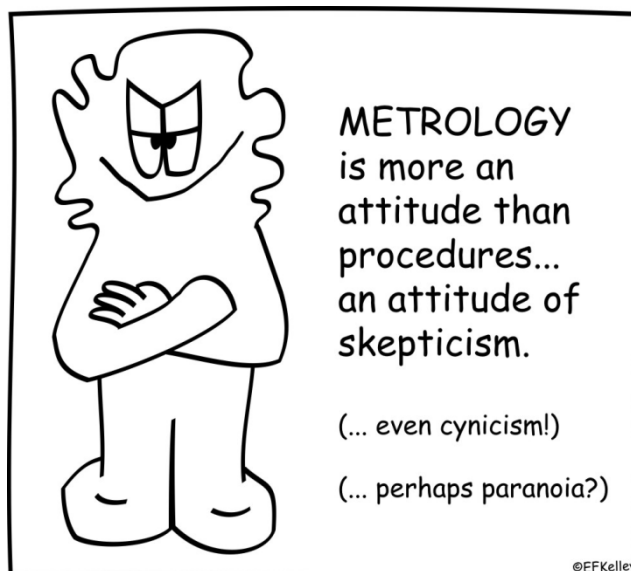
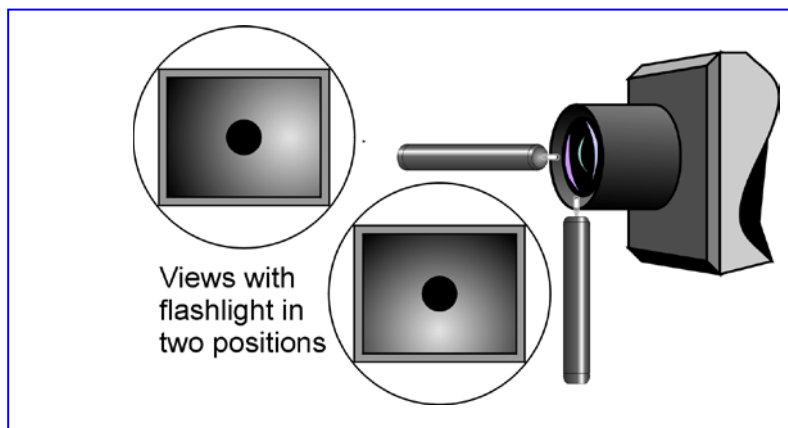




A15.6 FRAGILE DISPLAYS WITHOUT SPECULAR REFLECTIONS

If there is not a specular component (mirror-like producing a distinct-image) of reflection from the display surface and if no part of the surface of the display can be touched in any way, then it is difficult to determine when the display is exactly perpendicular to the optical axis of the LMD.

If the display surface has a sufficiently peaked haze component of reflection (not creating a distinct image but obviously brighter in the specular direction), then it may be possible to see a fuzzy reflection of a polystyrene foam cup with its bottom cut out over the lens to make the lens more visible in the reflection. Another trick is to place a point light source like a bare flashlight bulb at the center of the LMD lens with a small opaque mask to prevent light going back into the lens. Then attempt to see the fuzzy spot on the reflection of the display and align the display so that the fuzzy spot is centered in the LMD viewfinder—centered over the measurement aperture. If the LMD is on a rail so that it can be moved closer to the display, and the LMD is aligned parallel with the rail, it may be easier to do this with the LMD and light closer to the display than it will be when the measurement is made. Alternatively, you might be able to place the bulb just directly below the lens of the LMD (or to the left or right) and align the fuzzy spot directly above (or to the left or right of) the bulb.





B. TUTORIALS & DISCUSSIONS

This chapter of the appendix is a catch-all chapter to provide various tutorials regarding the measurement of light, some photometric calculations to help the reader gain familiarity with what most would consider to be as some very strange units (cd, lx, lm, etc.) and methods of optical analysis. Quite a few of us need to use photometry terms correctly. We hope this section helps. There are a number of study problems presented here. These are intended to be examined with pencil in hand, working with the material as the description develops.



B1 RADIOMETRY, PHOTOMETRY AND COLORIMETRY

Radiometry is the science of measuring electromagnetic radiation over its entire spectrum. Its definitions are codified in International System (SI) units---see www.physics.nist.gov/cuu/. In SI units, the total electromagnetic power is defined in Watts (W), and irradiance (flux density) is defined as the power per unit area (W/m^2) incident from all directions in a hemisphere onto the plane that bounds the hemisphere. Radiant intensity is the power per unit solid angle (W/sr). Here, the solid angle is defined either with respect to a point on the radiation source or a point on the detector; a unit solid angle is defined to subtend a unit area on a sphere of radius 1. Finally, radiance is the power per unit solid angle per unit projected area ($\text{W}/\text{sr}/\text{m}^2$). All these quantities have counterparts that are spectral densities on a wavelength-by-wavelength basis in which all the units become modified to include nanometers (nm) in the denominator. The status of the spectral quantities as densities implies that if you transform, for example, from wavelength λ to frequency ν , the corresponding densities are multiplied by $|d\lambda/d\nu|$ so as to preserve definite integrals. The study of light and vision depends on the above radiometric definitions. (Note the proper use of “radiation” rather than “light” for UV and IR. Light is visible but UV and IR radiation is mostly not visible.)

Photometry is the science of measuring visible light based upon the response of an average human observer. The primary unit of visible light power (**luminous flux**) used in photometry is the **lumen**. One watt of radiant flux at 555 nm is equivalent to a luminous flux of 683 lumens. Luminous flux (lumen) is defined as radiant flux weighted by the 1931 CIE Standard Observer function and can be calculated by the following formula

$$\text{Luminous flux in lumens } \Phi = k \int_{360}^{830} S(\lambda)V(\lambda)d\lambda \quad (1)$$

where:

$S(\lambda)$ = Absolute spectral radiant flux in W/nm

$V(\lambda)$ = The spectral luminous efficiency for photopic vision. It is based on the 1931 CIE standard observer human vision model having the spectral responsivity of $V(\lambda)$ for a field-of-view of 2° .

$k = 683 \text{ lm}/\text{W}$ = Conversion factor from watts to lumens at the peak of $V(\lambda)$

$d\lambda$ = Wavelength increment (nm)

As the equation shows, it is possible to measure light in the visible range with a filter/detector combination that matches the photopic function $V(\lambda)$ and get photometric quantities. This is the basic principle of luminance and illuminance meters. An alternate method, such as used with spectroradiometers, is to measure the spectral radiant flux and integrate the spectrum mathematically with $V(\lambda)$ to obtain the photometric quantities. From equations similar to this, you can get illuminance E (lx) from $S(\lambda)$ given as the spectral irradiance ($\text{W m}^{-2} \text{ nm}^{-1}$), and you can get luminance L (cd/m^2) from $S(\lambda)$ given as the spectral radiance ($\text{W sr}^{-1} \text{ m}^{-2} \text{ nm}^{-1}$).

There has been a tendency to associate the luminance with brightness, but this association is misleading. “Brightness” was at one time used for luminance, but that is no longer the case. Brightness is the visual sensation of human eyes, and the eye's response to light is nonlinear (see § B9), whereas luminance is linear (luminance meters have a linear response to light). More significantly, lights that are highly chromatic can appear brighter than white lights of the same luminance. The main experimental foundation of the $V(\lambda)$ function (which was already standardized by the CIE in 1924) was not brightness matching but flicker sensitivity. The visual system is far less sensitive to temporally alternating lights when these lights have the same luminance. By alternating two monochromatic lights and varying the intensity of one of them, equal luminance is defined as the condition of least sensitivity to the flicker, i.e., lowest temporal frequency for which the visual system fails to see the flicker. It happens that spatial acuity and certain of its corollaries (such as legibility of print) are



also determined principally by luminance.¹ Given that the luminance predominates in determining sensitivity to flicker and to spatial detail, luminance is almost certainly a basic visual channel, and luminance is an important aspect of light, quite apart from the colorimetric role of $V(\lambda)$ described below.

B1.1 PHOTOMETRY

Three of the most important terms used in photometry are luminance, illuminance and luminous intensity (see the following sections for more explanations). Although it would be logical to choose the lumen as the photometric base unit, the unit of luminous intensity, the candela, retains that role for reasons of tradition. The candela was defined as the luminous intensity of $1/60$ of 1 cm^2 of the projected area of a black body radiator operating at the temperature of the solidification of platinum (2045 K). This is no longer the definition. Since 1979 the candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12} \text{ Hz}$ and that has a radiant intensity in that direction of $(1/683) \text{ W sr}^{-1}$. The candela is defined in terms of the lumen by:

$$1 \text{ candela} = 1 \text{ lumen per steradian}$$

The lumen is the luminous flux emitted per unit solid angle from an isotropic point source whose luminous intensity is 1 candela. Most lamps that are manufactured are rated in total lumen output. The solid angle is measured in steradians, and a steradian is the solid angle (cone) at the center of a sphere of radius r that subtends an area r^2 on the surface of the sphere. Since the surface area of a sphere is $4\pi r^2$, the solid angle of a sphere is 4π steradians.

Luminance is the most commonly measured photometric quantity and is required whenever it is necessary have some quantitative indication of how bright an object can appear to the eye. Luminance is defined as the luminous flux emitted from a surface per unit solid angle per unit area in a given direction and it is therefore the luminous intensity per unit area. The unit of luminance is the **candela per square meter (cd/m^2)** in SI (metric) units (this unit was at one time called a “nit” but that is considered improper currently—the nit is a deprecated unit) or the **footlambert (fL)** in Imperial units.

$$1 \text{ cd/m}^2 = 1 \text{ lumen per steradian per square meter}$$

$$1 \text{ fL} = (1/\pi) \text{ lumens per steradian per square foot}$$

The conversion factors are

$$1 \text{ cd/m}^2 = 0.2919 \text{ fL} \quad (\pi \text{ ft}^2/\text{m}^2 = 0.2918635)$$

$$1 \text{ fL} = 3.4263 \text{ cd/m}^2 \quad (\text{m}^2/\pi \text{ ft}^2 = 3.426259).$$

Here the area (square meter or square foot) refers to the light-generating surface and the steradian refers to the solid angle subtended by the light detector from a point on the light-generating surface.

Illuminance is the term used to measure the luminous flux incident on a surface per unit area and is given in lumens/square-meters (lm/m^2). It is required when it is necessary to know how much light is falling on a surface, such as when illuminating a projection screen. The SI (metric) unit of illuminance is the **lux (lx)** or **footcandle (fc)** in Imperial units.

$$1 \text{ lux} \equiv 1 \text{ lx} \equiv 1 \text{ lumen / square meter}$$

$$1 \text{ footcandle} \equiv 1 \text{ fc} \equiv 1 \text{ lumen / square foot}$$

The conversion factors are

$$1 \text{ lx} = 0.0929 \text{ fc} \quad (\text{ft}^2/\text{m}^2 = 0.09290304)$$

$$1 \text{ fc} = 10.76 \text{ lx} \quad (\text{m}^2/\text{ft}^2 = 10.76391)$$

Luminous intensity (or “candlepower,” an obsolete term) is the luminous flux per unit solid angle emitted or reflected from a point. This is the quantity to describe the intensity of a light source in a specific direction. Since a point source is assumed, luminous intensity can be measured and used only at distances where the size of the source is negligible. LEDs are often characterized by luminous intensity and assumed to be point sources. The unit of luminous intensity is given in lumens/steradian (lm/sr) and it is called the **candela**. Table 1 lists important radiometric quantities, units, and their photometric equivalents.

¹ P. Lennie, J. Pokorny, and V. C. Smith, Luminance, J. Opt. Soc. Am. A, Vol. 10 (1993), pp. 1283-1293.

**Table 1.** Photometric and Radiometric Terms and Units

sr = steradian, lm = lumen, W = watt, m = meter, cd = candela, fL = footlambert, fc = footcandle

Radiometric Term	Radiometric Unit	Photometric Term	SI Unit	Imperial Unit
Radiant flux	watt (W)	Luminous flux	lumen (lm)	lumen (lm)
Radiant Intensity	watt/sr (W/sr)	Luminous intensity	candela (cd = lm/sr)	candela (cd = lm/sr)
Radiance	W/sr/m ²	Luminance	cd/m ²	footlambert (fL)
Irradiance	W/m ²	Illuminance	lux (lx = lm/m ²)	footcandle (fc)

Perfect reflecting diffuser: It is sometimes important to be able to transform illuminance as measured by an illuminance meter facing outward from a VDU screen into an equivalent screen luminance as measured by a luminance meter directed at a perfectly reflecting diffuser (Lambertian 100 % reflecting white surface) in the ambient light that was measured by the illuminance meter. If the screen were Lambertian with 100 % reflectance, and there was no absorbing faceplate, then there is a luminance equivalent to each illuminance unit (here, the symbol “ \leftrightarrow ” means “produces” or “is produced by”):

$$1 \text{ lx} \leftrightarrow (1/\pi) \text{ cd/m}^2 \text{ (for perfect Lambertian white surfaces only).}$$

The equivalent expression in Imperial units (or inch-pound units) avoid the $1/\pi$ factor—a simplification that encourages some to yet use the Imperial units to this day—this is not recommended in this document.

$$1 \text{ fc} \leftrightarrow 1 \text{ fL (for perfect Lambertian white surfaces only).}$$

To avoid the $1/\pi$ factor, people (in the past) used a direct luminance equivalent of 1 lx called the apostilb, but this is not an SI unit, and should be avoided except for historical reasons. For further conversion factors and other units of light measurements, see G. Wyszecki and W. S. Stiles, *Color Science* (Wiley, 1982), p. 251.

Do not confuse illuminance and luminance. Only for Lambertian materials are luminance and illuminance simply related by the equation $L = \rho E/\pi$. We don't have truly Lambertian materials, we only have quasi-Lambertian materials. See § B6 for more discussion.

Converting photometric units: Suppose you need to have the luminance expressed in cd/m², but it is given to you in fL, you have the table below, but get confused as to how to use it. Here is a simple way: Multiply by one, where the denominator has the unit that you want to eliminate, and the numerator has the unit you want to use. Thus, if you're given a screen luminance as 37.5 fL and you want SI units...multiply by one...

$$37.5 \text{ fL} * 1 = 37.5 \text{ fL} * 3.4263 \frac{\text{cd/m}^2}{\text{fL}} = 128 \text{ cd/m}^2$$

Similarly, given an illuminance of 24.9 fc, what is the illuminance in lux? ... multiply by one...

$$24.9 \text{ fc} = 24.9 \text{ fc} * 1 = 24.9 * 10.76 \frac{\text{lx}}{\text{fc}} = 268 \text{ lx.}$$

Table 2. SI (Metric) and Imperial Photometric Conversion Table

$\downarrow = \text{####} * \rightarrow$	cd/m ² (lm/sr/m ²)	fL (lm/sr/ft ² /π)	lx (lm/m ²)	fc (lm/ft ²)
1 cd/m ² = 1 lm/sr/m ²	1	0.2919		
1 fL = (1/π) lm/sr/ft ²	3.4263	1		
1 lx = 1 lm/m ²			1	0.09290
1 fc = 1 lm/ft ²			10.76	1
origin of number:	m ² /π/ft ² = 3.426259...	πft ² /m ² = 0.2918635...	m ² /ft ² = 10.76391...	ft ² /m ² = 0.09290304...
1 = \rightarrow	3.4263 $\frac{\text{cd/m}^2}{\text{fL}}$	0.2919 $\frac{\text{fL}}{\text{cd/m}^2}$	10.76 $\frac{\text{lx}}{\text{fc}}$	0.09290 $\frac{\text{fc}}{\text{lx}}$



B1.2 COLORIMETRY

Colorimetry is the scientific quantification and measurement of color. CIE tristimulus colorimetry is the most common system used to quantify the color of displays, and it is based on the assumption that any color can be matched by a suitable combination of three primary colors (“stimuli”)—generally red, green and blue. Once unit quantities of three primaries have been defined, the gains on these quantities needed to match a given light are called that light’s tristimulus values.

For any set of primaries in a matching experiment, the tristimulus values of monochromatic lights trace out three functions called the color-matching functions. From the observed linearity of human color matches, it follows that a change in primary lights is equivalent to a simple linear transformation of the color-matching functions for the first set of primaries. In 1931 the CIE standardized a single set of functions that no longer relied on which primaries were used in a particular matching experiment but summarized many experiments. The tristimulus values of a light in this system are called X , Y , Z , computed as wavelength integrals of a spectral density of the light being measured $S(\lambda)$ weighted by three visual sensitivities $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ and multiplied by a constant k . The constant k can convert radiometric watts to lumens, or it can be used to normalize the tristimulus values to 100 with no units (some have normalized to one instead). See the Table 3 for definitions of the tristimulus values. The associated tristimulus value Y is the only one that can be associated with photometric quantities—see Table 4.

Any two lights that have the same values of X , Y , and Z are defined to match (be the same color) according to the 1931 standard observer. Incidentally, the function $\bar{y}(\lambda)$ is exactly equal to the function $V(\lambda)$ defined in 1924 for photometry. [See the original CIE publication on color for more information, CIE Publication No. 15.2, Colorimetry (1986). For further details on the history of the 1931 CIE system and how the previously defined photometric $V(\lambda)$ was incorporated, see H. Fairman, M. Brill, & H. Hemmendinger, *Color Res. Appl.* 22 (1997), 11-23.]

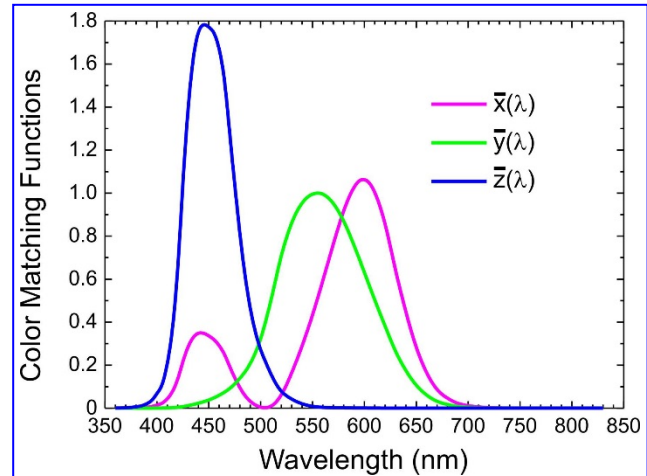


Table 3. TRISTIMULUS VALUES

General Case, Not Normalized

$S(\lambda)$ is illumination relative spectral density in $(\text{nm})^{-1}$, k is any convenient constant, e.g., $k = 1$

$$X = k \int_{360 \text{ nm}}^{830 \text{ nm}} S(\lambda) \bar{x}(\lambda) d\lambda, \quad Y = k \int_{360 \text{ nm}}^{830 \text{ nm}} S(\lambda) \bar{y}(\lambda) d\lambda, \quad Z = k \int_{360 \text{ nm}}^{830 \text{ nm}} S(\lambda) \bar{z}(\lambda) d\lambda$$

NORMALIZED TRISTIMULUS VALUES —BASED ON WHITE POINTS

Normalization shown at 100, any other normalization constant may be used as desired.

For Reflection and Transmission:

$\beta(\lambda)$ is relative reflection or transmission spectral density, $S(\lambda)$ is illumination spectral density

$$X = k \int_{360 \text{ nm}}^{830 \text{ nm}} \beta(\lambda) S(\lambda) \bar{x}(\lambda) d\lambda, \quad Y = k \int_{360 \text{ nm}}^{830 \text{ nm}} \beta(\lambda) S(\lambda) \bar{y}(\lambda) d\lambda, \quad Z = k \int_{360 \text{ nm}}^{830 \text{ nm}} \beta(\lambda) S(\lambda) \bar{z}(\lambda) d\lambda$$

$S(\lambda)$ in any units
(W/nm...?...)

No units for X , Y , Z ,
maximum of 100 for Y

$$k = 100 \left[\int_{360 \text{ nm}}^{830 \text{ nm}} S(\lambda) \bar{y}(\lambda) d\lambda \right]^{-1}$$

For Emissive Displays

$S(\lambda)$ is spectral density of display white, $C(\lambda)$ is spectral density of displayed color



$X = k \int_{360 \text{ nm}}^{830 \text{ nm}} C(\lambda) \bar{x}(\lambda) d\lambda, \quad Y = k \int_{360 \text{ nm}}^{830 \text{ nm}} C(\lambda) \bar{y}(\lambda) d\lambda, \quad Z = k \int_{360 \text{ nm}}^{830 \text{ nm}} C(\lambda) \bar{z}(\lambda) d\lambda,$		
$S(\lambda)$ and $C(\lambda)$ in any (but same) units (W/nm...?...)	No units for X, Y, Z , maximum of 100 for Y	$k = 100 \left[\int_{360 \text{ nm}}^{830 \text{ nm}} S(\lambda) \bar{y}(\lambda) d\lambda \right]^{-1}$

Over the years the CIE standardized several color spaces derived from the 1931 XYZ space, but in which equal distances in different parts of the space represented perceptual differences that were approximately equal. These were called uniform color spaces and were especially useful in assessing color gamuts and the magnitudes of colorimetric errors.

Below is a summary of various CIE color spaces that have been used to evaluate displays. For detailed information including tables of color-matching functions, see *Color Science: Concepts and Methods, Quantitative Data and Formulae*, Gunter Wyszecki and W.S. Stiles, 2nd Edition (1982, John Wiley & Sons).

Table 4. PHOTOMETRIC Y (Only Y is the photometric quantity.)	
$S(\lambda)$ is illumination spectral density	
$Y = k \int_{360 \text{ nm}}^{830 \text{ nm}} S(\lambda) \bar{y}(\lambda) d\lambda$, where $k = 683 \text{ lm/W}$	
if $S(\lambda)$ is in units of ...	then Y is in units of ...
radiant flux (W/nm)	luminous flux (lm)
radiant intensity (W/nm/sr)	luminous intensity (cd)
radiance (W/nm/sr/m ²)	luminance (lm/sr/m ² = cd/m ²)
irradiance (W/nm/ m ²)	illuminance (lm/m ² = lx)

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



1931 x, y - CIE Chromaticity Values: These values are two-dimensional Cartesian coordinates that derive from X, Y, Z tristimulus values, in such a way that lights with the same relative spectrum but different intensities occupy the same (x, y) point. Hence the chromaticity values represent the colorimetric aspects of a light that are independent of its intensity. The 1931 chromaticity values are designated as x, y, z , and they are the ratios of the tristimulus values X, Y and Z in relation to the sum of the three.

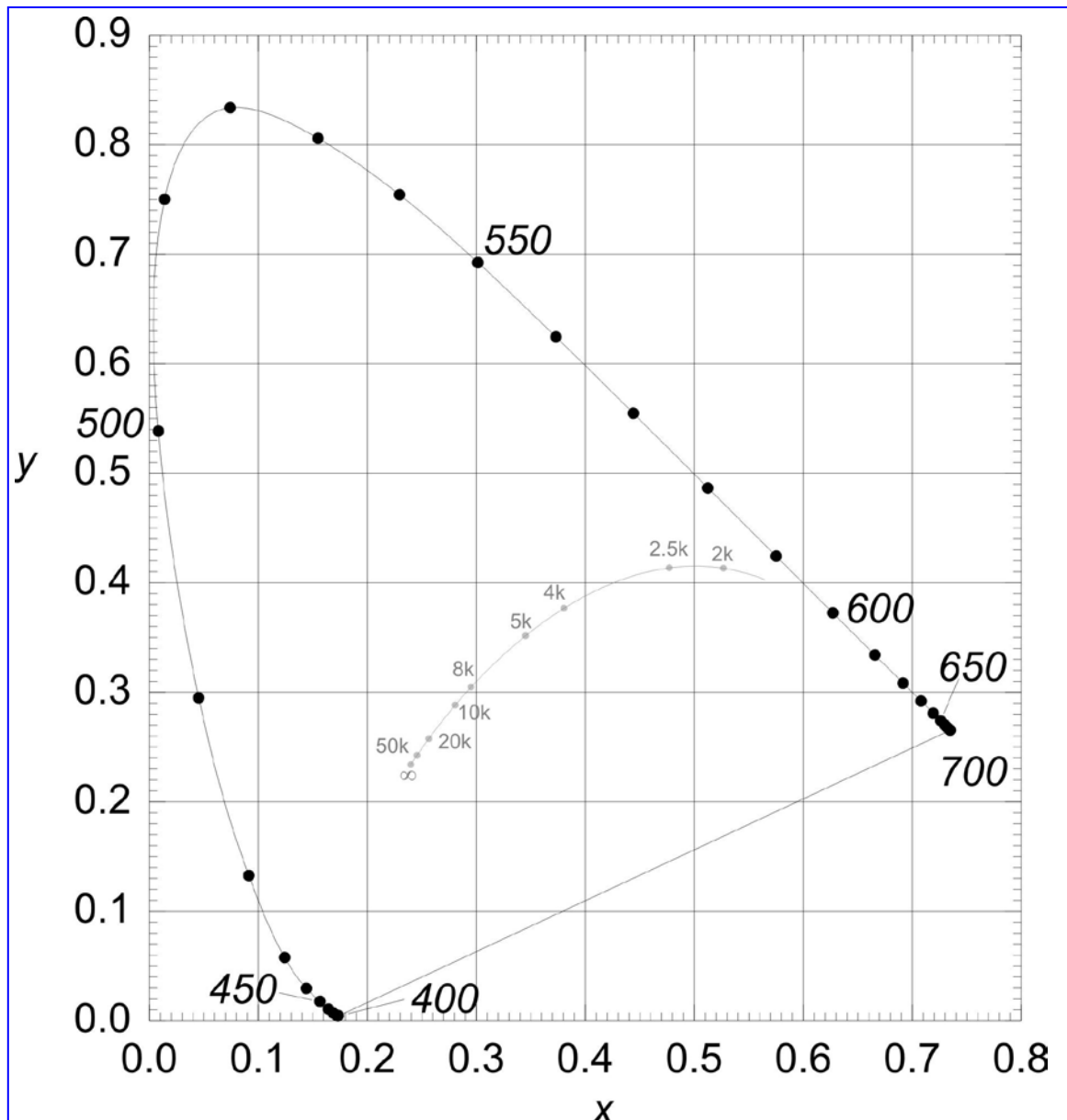
$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z}, \quad z = \frac{Z}{X+Y+Z}, \quad \text{where } x + y + z = 1.$$

Conversely,

$$X = \frac{x}{y} Y, \quad Y, \quad Z = \frac{z}{y} Y.$$

Here, Y can be any photometric quantity, flux, intensity, luminance, etc. Because z is redundant in chromaticity description, it is usually suppressed in favor of a two-dimensional plot of (x, y) .

In the CIE 1931 plot the curved line within the spectrum locus is the Planckian locus marked in temperatures of thousands of kelvins. The spectrum locus is labeled in increments of 50 nm. This is the color of white as the temperature of a (perfect) emitter is increased to an infinite temperature. This observation gives rise to the concept of color temperature as being a way to characterize the “level” of white.





1960 u, v — Uniform Chromaticity Scale (UCS). An early uniform-color space, one of whose drawbacks was that it had only two dimensions. This space—a proper chromaticity space derived from linear combinations of X, Y, Z , is now used only for calculating correlated color temperature (CCT; see Glossary).

$$u = u' \text{ and } v = 2v'/3, \text{ where } u', v' \text{ are the 1976 UCS values below.}$$

1976 u', v' — Uniform Chromaticity Scale (UCS). Proper chromaticity space derived from linear combinations of X, Y, Z . $\Delta u'v'$ is sometimes used as a color-shift metric when one wants to ignore intensity variations. In the plot the curved line within the spectrum locus is the Planckian locus marked in temperatures of thousands of kelvins. The spectrum locus is labeled in increments of 50 nm.

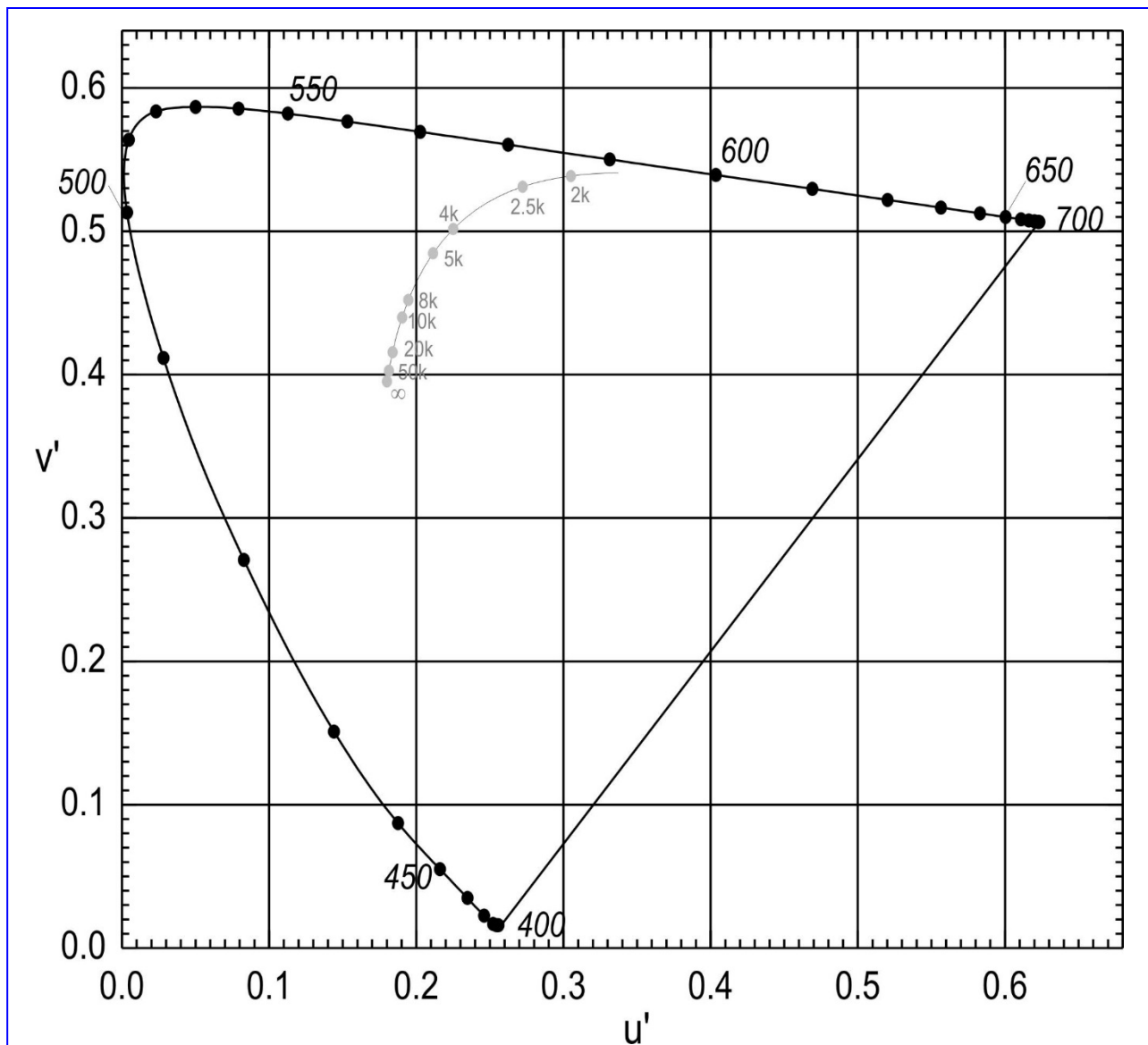
$$u' = \frac{4X}{X + 15Y + 3Z} \quad \left(= \frac{4x}{3 + 12y - 2x} \right)$$

$$x = \frac{9u'}{6u' - 16v' + 12}$$

$$v' = \frac{9Y}{X + 15Y + 3Z} \quad \left(= \frac{9y}{3 + 12y - 2x} \right)$$

$$y = \frac{4v'}{6u' - 16v' + 12}$$

$$\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}$$





1976 CIELUV — Currently standardized three-dimensional uniform-color space. [Commission Internationale de l'Éclairage, Publication CIE No. 15:2004, *Colorimetry*, Central Bureau of the CIE, Vienna, 2004.]. Implicit in this space is a model of the nonlinearity of the eye, and also of chromatic adaptation to a light (typically D65 or the white point of the display) characterized by values with subscripts “n” below. The lightness is defined as:

$$L^* = 116 f(Y / Y_n) - 16$$

where:

$$f(Y / Y_n) = (Y / Y_n)^{1/3}, \quad \text{if } Y / Y_n > (6/29)^3$$

else

$$f(Y / Y_n) = (841 / 108) Y / Y_n + 4 / 29, \quad \text{if } Y / Y_n \leq (6/29)^3.$$

The chromaticity coordinates and color difference metric are:

$$u^* = 13L^* (u' - u'_n),$$

$$v^* = 13L^* (v' - v'_n).$$

$$\Delta E_{uv}^* = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2},$$

$$\Delta L^* = L_1^* - L_2^*, \quad \Delta u^* = u_1^* - u_2^*, \quad \Delta v^* = v_1^* - v_2^*$$

1976 CIELAB — Currently standardized three-dimensional-uniform color space [Commission Internationale de l'Éclairage, Publication CIE No. 15:2004, *Colorimetry*, Central Bureau of the CIE, Vienna, 2004.]. Implicit in this space is a model of the nonlinearity of the eye, and also of chromatic adaptation to a light (typically D65 or the white point of the display) characterized by values with subscripts “n” below. The lightness is defined as

$$L^* = 116 f(\underline{Y} / Y_n) - 16.$$

The chromaticity coordinates are:

$$a^* = 500 [f(X / X_n) - f(Y / Y_n)],$$

$$b^* = 200 [f(Y / Y_n) - f(Z / Z_n)],$$

where the function $f()$ acting on any variable q is defined as:

$$f(q) = q^{1/3}, \quad \text{if } q > (6/29)^3,$$

else

$$f(q) = (841 / 108) q + 4 / 29, \quad \text{if } q \leq (6/29)^3.$$

A difference metric is also defined:

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2},$$

$$\Delta L^* = L_1^* - L_2^*, \quad \Delta a^* = a_1^* - a_2^*, \quad \Delta b^* = b_1^* - b_2^*.$$

Both CIELAB and CIELUV color spaces were simultaneously adopted and thereafter retained as equally preferred standards by the CIE [see CIE Publication 15.2, *Colorimetry*, First Edition (CIE, 1976) and Second Edition (CIE, 1986)]. However, display technologists historically preferred CIELUV. This preference is based on the fact that CIELUV has a proper chromaticity space (with coordinates u^*/L^* , v^*/L^*), in which any additive mixture of two lights shows up on the line segment between them in this space. This feature, which is not shared by CIELAB, offers a convenient portrayal of composition of color in additive systems such as self-luminous displays. Admittedly, the CIELAB space has been recently selected by some display technologists as being more nearly uniform with respect to small color differences. However, CIELUV remains a documented CIE space and is attractive because of its convenience and historical precedent. The present document does not recommend CIELUV as being preferable to CIELAB or to other color-difference formulas, but uses CIELUV in sample calculations as a color space sufficient for the measurements at hand.

A note is due about the uses and perceptual interpretations of ΔE and $\Delta u'v'$. The quantity ΔE can be interpreted as a measure of the number of just-noticeable differences (JNDs; see Glossary) between two displayed colors with given

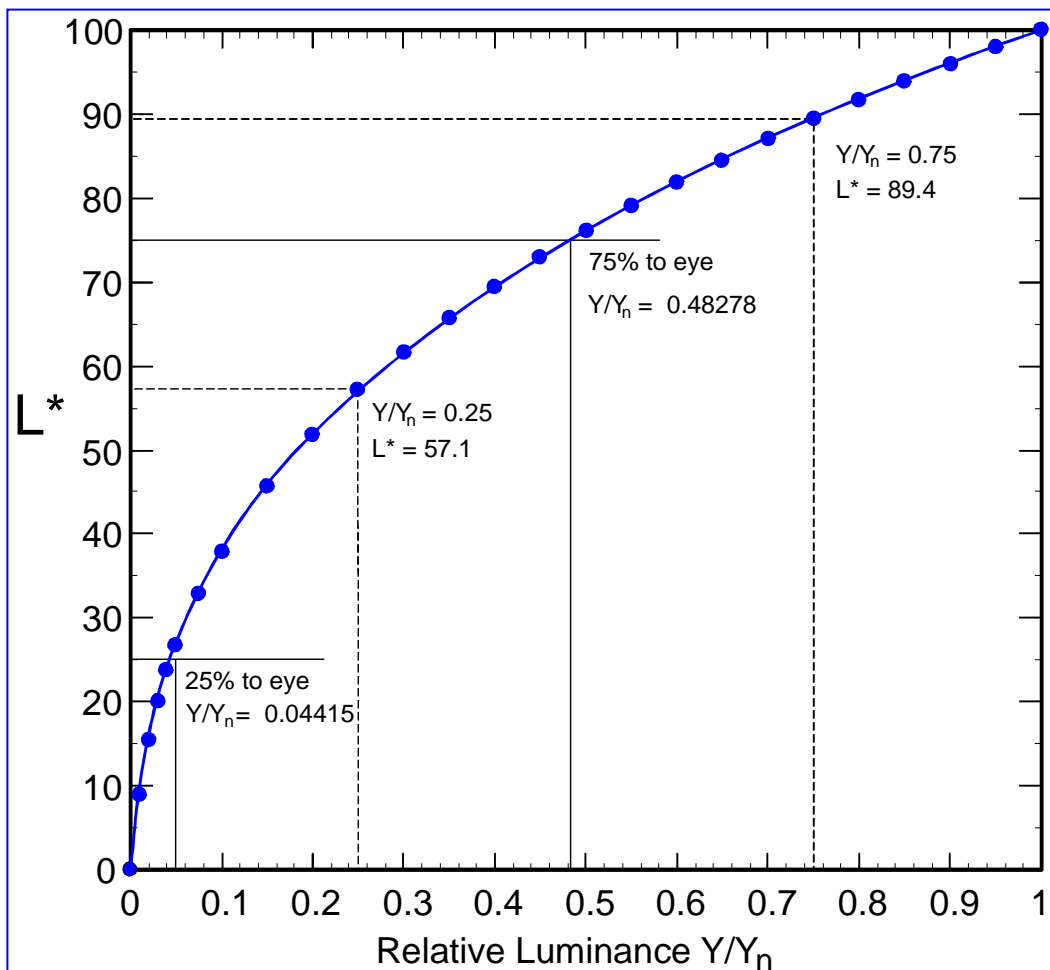
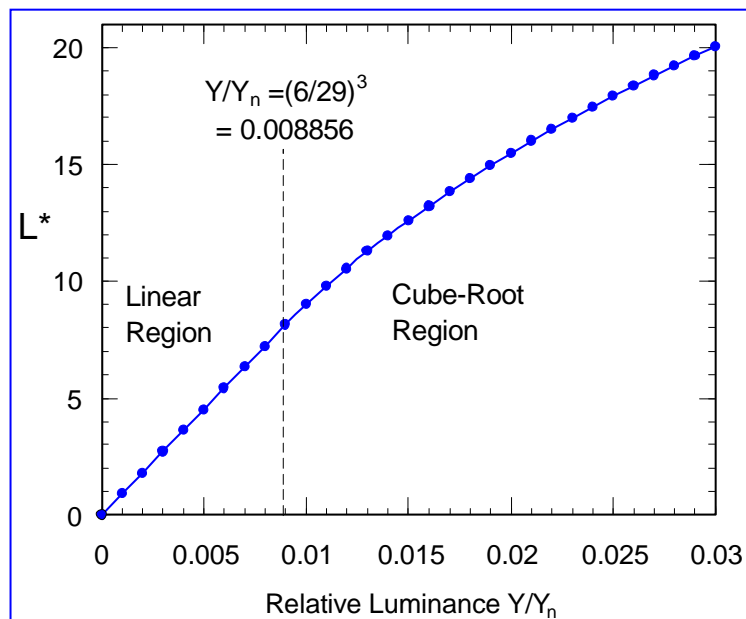


tristimulus values. The fact that ΔE is a Euclidean metric in a given color space (CIELAB or CIELUV) suggests an interpretation of that distance as a perceptual magnitude, measured in units of JNDs. Although the discriminability of two colors depends on viewing conditions, and the experimental basis of CIELAB or CIELUV uses special viewing conditions (see Wyszecki and Stiles, 1982), ΔE is interpreted as a general-purpose color metric. In display technology, we find ΔE used, e.g., to quantify dependencies of color on screen position and viewing direction. However, ΔE is not used to describe the distance between two colors that arise on displays with different white points. It is tacitly specified that the same (X_n, Y_n, Z_n) triplet (nominally the same observer adaptation state) be used for each color in a comparison yielding a ΔE value.

The quantity $\Delta u'v'$ is not so easy to interpret perceptually as ΔE but is useful when one wants to set independent tolerances on luminance and chromaticity. [An alternative approach adaptable to any color space but which has not been used extensively is M. H. Brill and L. D. Silverstein, "Isoluminous color difference metric for application to displays," *Society for Information Display International Symposium* (May 2002), *Digest of Technical Papers*, Vol. 38, No. 2, pp. 809-811.]

A color shift of $\Delta u'v' = 0.004$ will be discernable if the two color patches are touching, and a color shift of

$\Delta u'v' = 0.04$ will be discernable on two separate displays. Suppose, for example, that the luminance uniformity on a screen is subjected to a fairly loose tolerance (because human vision is insensitive to luminance variations with low spatial frequencies). If a tight chromatic tolerance is set with respect to u^* and v^* (to reflect high sensitivity to chroma variations at low spatial frequencies), then that tolerance will be driven by luminance variations for any chromaticities but that of the white point. This will impose de facto a tight tolerance on luminance uniformity. However, if a tight chromatic tolerance is set with respect to u' and v' (as it is with $\Delta u'v'$), the





sensitivity of vision to isoluminous color variations at low spatial frequencies is accommodated without imposing a needless restriction on the luminance uniformity.

A comment is in order about L^* , which is the same in both CIELUV and CIELAB. In the figures to the right we show how L^* depends upon the ratio of the luminance Y to the luminance of white Y_w . The linear portion [from $Y/Y_w = 0$ to $Y/Y_w = (6/29)^3$] smoothly matches the cube-root portion [the first derivative is continuous across $Y/Y_w = (6/29)^3$]. The top figure shows the region about the linear portion. The bottom figure shows the entire range of $Y/Y_w \leq 1$. See § B9 Nonlinear Response of the Eye for a discussion of the bottom figure.

B1.2.1 CORRELATED COLOR TEMPERATURE (CCT).

Manufacturers and users often want a single-number summary of the color of a light source or of a display. Because many natural light sources resemble black-body radiators, a natural summary number is the temperature of the black-body radiator closest in color to the light source (or display) in question. Accordingly, correlated color temperature (CCT) is defined as the temperature (in kelvin) of the black-body radiator whose chromaticity is closest to the chromaticity of a particular light (e.g., from a display screen) as measured in the 1960 CIE (u , v) uniform chromaticity space. Despite the fact that the 1960 (u , v) space has been superseded by other uniform-color spaces (see below), the CCT continues to be defined in the earlier space, to afford consistency of description to light sources over time.

An algorithm for computing CCT, either from 1931 CIE (x , y) coordinates or from 1960 (u , v) coordinates, appears in [7] G. Wyszecki and W. S. Stiles, *Color Science*, Second Edition, Wiley, 1982, pp. 224-228, where a graphical nomogram also appears. Alternatively, a successful numerical approximation has been derived by C. S. McCamy, *Color Res. Appl.* **17** (1992), pp. 142-144 (with erratum in *Color Res. Appl.* **18** [1993], p. 150). Given CIE 1931 coordinates (x , y), McCamy's approximation is

$$\text{CCT} = 437 n^3 + 3601 n^2 + 6861 n + 5514 ,$$

where

$$n = (x - 0.3320)/(0.1858 - y).$$

This approximation (the second of three he proposes) is close enough for any practical use between 2000 and 10,000 K.

In units of 1960 (u , v) chromaticity, it is agreed that the concept of CCT has little meaning beyond a distance of 0.01 from the Planckian locus [see A. Robertson, *J. Opt. Soc. Am.* **58** (1968), 1528-1535], where the distance is specified by

$\Delta uv = \sqrt{(u_1 - u_2)^2 + (v_1 - v_2)^2}$. However, industrial applications define CCT from 0.0175 (u , v) units above the Planckian locus to 0.014 (u , v) units below this locus.

Besides the unit of 1960 (u , v) distance, another unit is also commonly used to quantify distance of a given light from the black-body locus. This is the minimum perceptible color difference (MPCD), defined as a distance of 0.004 (u , v) units. The value 0.004 was introduced in the early days of color television to specify a minimum perceptible difference in (u , v) under not-too-critical conditions (see W.N. Sproson, *Colour Science in Television and Display Systems*, Adam-Hilger, 1983, page 42). This figure is often quoted in the lighting industry and is now also applied to the distance metric in

the (u' , v') color space $\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}$ [see P. Alessi, *Color Res. Appl.* **19** (1994), 48-58]. A distance of 0.04 in (u' , v') would be considered to be noticeable if the colors were separated such as each color being displayed on a different screen in different parts of the room, whereas the threshold distance 0.004 refers to two colored areas that are touching each other on the same screen.

The above history notwithstanding, CCT as a metric for color error has the following problems:

1. CCT is sometimes referred to as "color temperature," but the latter isn't even defined for a light unless that light's chromaticity lies on a particular curve---the black-body locus---in chromaticity space.
2. CCT doesn't tell nearly the whole story about a color error: Any chromaticity shift that lies on an iso-temperature line [see Wyszecki and Stiles, *Color Science*, 2nd ed., Wiley 1982, p. 225] has zero error in the metric.
3. Correlated color temperature is highly nonlinear in perceptual effect. For example, points in the neighborhood of (x, y) = (0.24, 0.235) have CCT values that vary millions (even billions) of kelvins, for that region contains the limit of infinite color temperature.

Some experiments have shown (ibid., pp. 174-175) that inverse color temperature is approximately uniform in perceptual effect, but $\Delta(1/T)$ is also not a good metric because of reasons 1 and 2 above. A much more visually uniform error metric is $\Delta u'v'$.



B2 POINT SOURCE, CANDELA, SOLID ANGLE, $I(\theta, \phi)$, & $E(r)$

Abstract: We look at a point source of light which naturally gives rise to the concept of solid angle whereby we can see the reasonability of the candela as a unit of light measurement. Luminous intensity I and illuminance E are also defined and considered.

Consider a point source of light that emits rays of light or light energy uniformly in all directions. Consider a small area A of a sphere of radius r that is centered on the point source of light. Since light travels in straight lines (rays), the bundle of rays going through the area A will, in effect, project that area onto larger diameter spheres. This cone that is centered at the point source and subtends the area A will always contain the same rays of light no matter how far away we are from the point source. We want a metric to specify how much of a spread this cone constitutes. The metric to use is the **solid angle** which is the ratio of the spherical area A to the square of the radius

$$\omega = A / r^2 . \quad (1)$$

The solid angle is manifestly unitless, but it is given a unit: the steradian with abbreviation sr. We speak of solid angles in steradians; for example, the solid angle of an entire sphere is 4π sr.

Should this be an uncomfortable definition for the first time reader, note that it is very similar to radian measure of an arc, we might think of it as a three-dimensional angle. In a plane, an arc of length l at radius r along a circle is subtended by an angle $\theta = l/r$, where θ is in radians, abbreviated rad. An entire circle has a radian measure of $\theta = 2\pi$. Often the unit rad is left off, it is understood to be there, we could have said $\theta = 2\pi$ rad as well. By the way, to convert to degrees we use: $\theta[\text{in degrees}] = 360^\circ \theta / 2\pi$. Extending this to three dimensions by similarity, we express the solid angle as $\omega = A / r^2$, which is a measure of the subtense of a spherical area from a point in space just as we express the angle as $\theta = l/r$ which is a measure of the subtense of a circular arc from a point in space. The solid angle is the three-dimensional angular cone that subtends a spherical area A just as the angle (in radians) is a (two-dimensional) angle that subtends a circular arc length.

Note that the area A used in the solid-angle determination is the area on the surface of a *sphere* not a planar area. However, for radial distances large compared to the maximum linear width of a planar area, the planar area can be used with little error. What is the difference between the area of a disk and the area of a spherical cap of the same diameter? Consider a sphere of radius r centered in a spherical coordinate system, and a spherical cap centered on the polar axis. Suppose θ is the angle subtended between the polar axis and the outside diameter of the cap. The area of the spherical cap can be shown to be

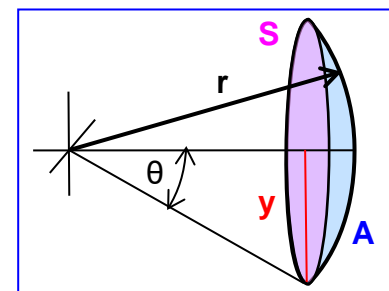
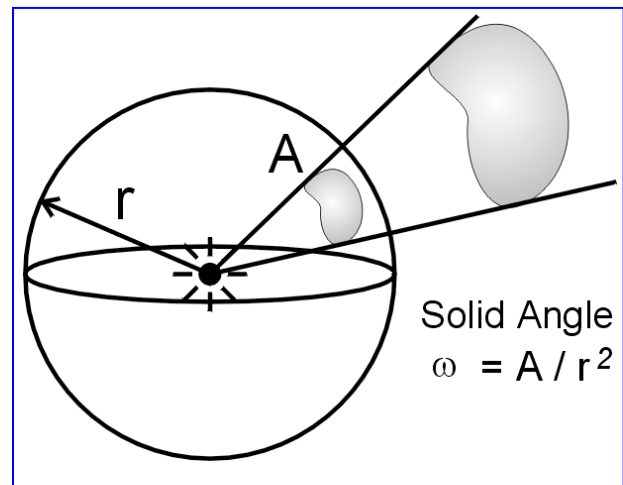
$$A = 2\pi r^2(1 - \cos\theta). \quad [\text{Spherical Cap}] \quad (2)$$

Associated with this cap is a planar disk defined by the diameter of the spherical cap. The radius of this disk is $y = r \sin\theta$, and its area is $S = \pi r^2 \sin^2\theta$. For small angles such that $\sin\theta = \theta$ is an acceptable approximation, these two areas are the same (expand the cosine to prove).

How do we specify the intensity of the point source? One way is the amount of **luminous flux** Φ (measured in lumens, lm) emanating from the point. This is a measure of the amount of light coming from the point source in all directions combined. Luminous flux is kind of like a “visible light watt,” it is proportional to the visible power of the emitted light. Another way to express the amount of light from the point source is by taking the ratio of the luminous flux Φ_A (in lm) that hits area A and the solid angle $\omega = A / r^2$ (in sr). This ratio is called the **luminous intensity**

$$I = \Phi_A / \omega = \Phi_A r^2 / A , \quad (3)$$

and has units of lm/sr, which is called a candela with abbreviation cd. In general, the luminous intensity is a function of the direction of emission $I = I(\theta, \phi)$, but for our purposes in this problem, we will assume it is a constant. For our uniformly emitting point source what is the luminous intensity? Divide the total luminous flux Φ by the solid angle of a sphere:





$I = \Phi/4\pi = \text{constant}$ (units are $\text{lm/sr} = \text{cd}$). Now, let's think about the light hitting area A . The luminous flux hitting A (number of lumens hitting A) is $\Phi_A = I\omega$. That flux is spread uniformly over the entire area A . This raises the need for another convenient metric of light, the **illuminance** E which is the number of lumens per unit area hitting A ; it has units of lm/m^2 , which is called a lux, and the unit's symbol is lx. In our case here, the illuminance is the quotient of the luminous flux hitting the area A :

$$E = \Phi_A/A = I\omega/A = I/r^2 [\text{lm/m}^2]. \quad (4)$$

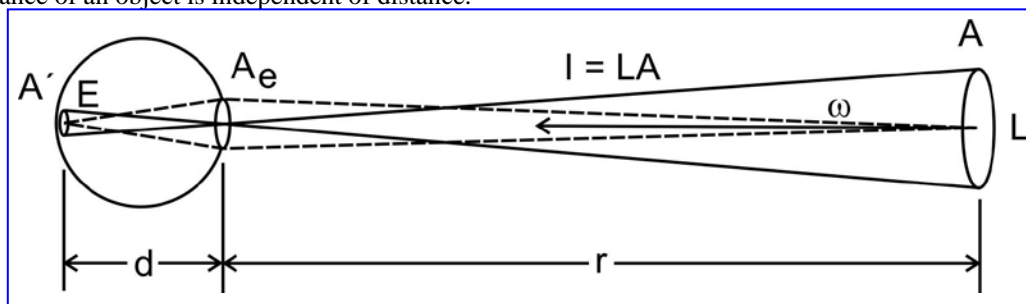
(Although the luminous intensity has units of lm/sr , we often write equations like this where we have canceled out the steradians but only keep track of that in our minds. To indicate the correct units or remind the reader of the correct units often one will find the units expressed in brackets after the equation to be sure to be clear. Some people deliberately add a quantity $\Omega_0 = 1 \text{ sr}$ to the equations in order to keep track of the steradians. In such a case $I = \Phi/4\pi \Omega_0$, $\Omega = \Omega_0 A/r^2$, $E = \Omega_0 I/r^2$, etc.) Things like luminous intensity, candelas, illuminance, and the like can be very confusing for the novice (even for the not-so-novice). One of the best ways to help to remove the confusion is to be able to express units of light measurement in their most fundamental units, $\text{lx} = \text{lm/m}^2$, $\text{cd} = \text{lm/sr}$, etc., and carefully keep track of these fundamental units as these quantities are used in equations. Thinking in terms of the units as well as the names of these quantities should make things easier.

PROBLEM: Suppose we are given the luminous flux $\Phi = 10,000 \text{ lm}$ of a point source that emits light uniformly in all directions, and we have a card of area $A = 0.01 \text{ m}^2$ ($100 \text{ mm} \times 100 \text{ mm}$) placed a distance $d = 0.5 \text{ m}$ away from the point source; what is the luminous intensity of the point source, the illuminance on the card, and the luminous flux on the card?

Provided d is large compared with the size of the card (and it is in this example), we can assume that the area A is the same as the area of the card projected on a sphere of radius d and use the formalism derived above. (Otherwise we would have to use calculus to perform the integration over the area A and this we will do in another problem below.) The solid angle of the card is $\omega = A/d^2 = 0.040 \text{ sr}$. The luminous intensity of the point source is $I = \Phi/4\pi = 795.8 \text{ cd} [\text{lm/sr}]$. The luminous flux (number of lumens) Φ_A on A is $\Phi_A = I\omega = 31.83 \text{ lm}$, whereby the illuminance on area A is $E = \Phi_A/A = I\omega/A = I/d^2 = 3183 \text{ lx} [\text{lm/m}^2]$. Notice that this is exactly the same as the luminous flux Φ times the fraction that the area A is of the radius of a sphere of diameter d : $\Phi_A = \Phi(A/4\pi d^2)$ which is what we get if we do all the algebra: $\Phi_A = EA = (I/r^2)A = (\Phi/4\pi r^2)A = \Phi A/4\pi r^2$ using $r = d$.

B3 LUMINANCE $L(z)$ OF UNIFORM AREA

Problem: Calculate the luminance as a function of position as we move away from a uniformly illuminated wall and show that the luminance of an object is independent of distance.



We can consider a number n of point sources each having luminous intensity I_k in candelas ($\text{cd} = \text{lm/sr}$) distributed evenly throughout an area A . Assume that there are so many of them that we can't resolve the individual illuminants with our eyes so that the surface appears uniform. The total luminous intensity from the area A is

$$I = \sum_{k=1}^n I_k. \quad (1)$$

The more point sources we cram into that area the brighter that area will appear to our eyes. The number of these sources (how many candelas) per unit area is called the **luminance** and has units $\text{cd/m}^2 = \text{lm sr}^{-1} \text{ m}^{-2}$. This unit was at one time called a nit, but that usage is no longer considered proper—the nit is a deprecated unit. (Isn't that great?! So instead of saying a one syllable "nit" we have to say a mouthful, the seven syllable phrase "candelas per meter squared.") Avoid using



brightness when you mean luminance. Luminance is a unit of measure, a quantitative value. Brightness is subjective. Something that may be considered bright at night may be perceived as not so bright during the day (e.g., the moon). Consider a source with constant luminance, the perception of brightness changes depending upon the ambient conditions, whereas the luminance of that source remains the same (assuming the environment doesn't affect the light output of the source).

Another way to define luminance is by using infinitesimals. Consider a small area dA perpendicular to the line of sight that emits light with luminous intensity dI . The ratio of the luminous intensity to the area is defined as the luminance:

$$L = dI/dA \quad (A \text{ perpendicular to line of sight}). \quad (2)$$

This means that when we are talking about small areas that are far away from the observation point ($A \ll r^2$) then we can say to a good approximation

$$L = \frac{I}{A}, \text{ or } I = LA \quad (\text{long-distance approximation, } A \text{ perpendicular to line of sight}). \quad (3)$$

If the area A is inclined an angle of θ to the line of sight (or line of measurement), then the apparent area is reduced by $\cos \theta$ (see § B4) and we have

$$I = LA \cos \theta \quad (\text{long distance approximation}), \quad (4)$$

or in terms of small elements

$$dI = L dA \cos \theta. \quad (5)$$

These relations will be found to be useful in the rest of these problems. The relationships expressed in Eqs. (4) and (5) are true in general even for non-Lambertian materials. [For non-Lambertian materials the angles defining the observation direction enter in $I(\theta, \phi) = L(\theta, \phi) A \cos \theta$.] Now, let's consider what the eye sees; how does the luminance of an object change with distance?

Imagine looking at the area A (such as described above) having a luminance of L with the eye at a distance r from the area, where r is much larger than the size of the area viewed $r^2 \gg A$. The lens of the eye focuses that area down to an area A' on the retina of the eye. Let's assume that the illuminance on the retina for this configuration is E . The size of the area on the retina depends upon the distance from the source. Let A_e be the aperture area of the eye, and suppose the distance from the center of the lens of the eye to the retina is d . How much light enters the eye? The luminous intensity from the area A is simply $I = LA$ for long distances. Then the light entering the eye (the luminous flux) is $\Phi = I\omega$, where ω is the solid angle of the aperture of the eye, $\omega = A_e/r^2$, or $\Phi = LAA_e/r^2$. That light is spread over the image A' so that the illuminance on the retina is $E = \Phi/A'$. From simple geometry consideration, the size of the area of the image is proportional to the square of the distances involved: $A' = Ad^2/r^2$. It is the illuminance on the retina that we want to determine, i.e., the lumens per unit area; it is this illuminance that gives the perception of luminance. Putting these equations together we find $E = LA_e/d^2$, which is independent of distance r that the eye is from the area. We could have simply reasoned this way: The image size at the retina goes as $1/r^2$, but the amount of light entering the eye goes down as $1/r^2$. The ratio of the two remains a constant, thus the luminance is independent of distance.

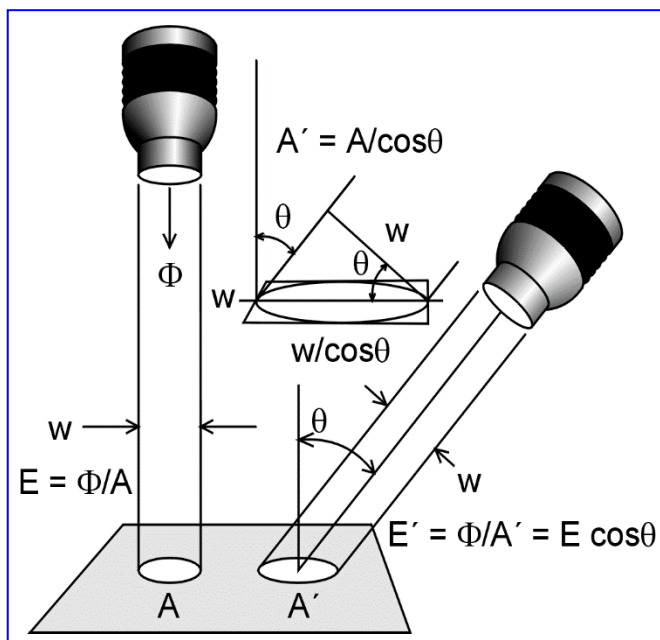
(NOTE: Many refer to luminance as the objective measure of subjective brightness. While this may be somewhat true when comparing the same colors, it is not true in general, and it is easy to see. Place three bars of primary colors on the screen of a display—e.g., RGB—and adjust the brightness of the bars so that they appear to have the same brightness to the eye. The luminances will not be the same: Green will have a much greater luminance than the red and blue. Now, put an identical word with black letters in each of the color bars and adjust the brightness of the bars so that the words are about as readable in each color—you might have to step back from the screen so they will be a little fuzzy. When you measure the luminance now, you will find it to be more nearly the same for each color. If the luminances are adjusted to be the same, then the green will appear to be very dark compared to the blue and red.)



B4 SPOTLIGHT VS. ANGLE — $\cos(\theta)$

Problem: Show that when a spotlight hits a surface the illuminance upon the surface changes as $\cos\theta$ where θ is the angle of the source from the perpendicular of the surface for a distant source like a spotlight (or the setting sun if you are on the moon).

Consider a spotlight having a uniform parallel beam of width w , cross-section area A , and luminous flux Φ in lumens (lm). The illuminance upon a surface when the beam is perpendicular to that surface is $E = \Phi/A$ (in lx = lm/m²). If the direction of the spotlight is changed to an angle θ from the perpendicular, then the area of the surface A' illuminated becomes more elongated as the angle increases (that area becomes infinite when the beam lies in the plane of the surface, $\theta = 90^\circ$). The dimension of the beam orthogonal to the plane of the angle and the perpendicular is still w , but the dimension of the beam in the plane of the angle becomes $w/\cos\theta$, see the figure. The areas are related by $A' = A/\cos\theta$. The same amount of light (luminous flux) Φ is being spread over a larger area, so that the illuminance becomes less: $E' = \Phi/A' = E\cos\theta$. Thus, the illuminance from a beam of light falls off as the cosine of the angle from the normal.



B5 GLOWWORM & DETECTOR, $I(\theta, \phi)$, $J=kF$

Problem: Given a nonuniform source producing a luminous intensity $I(\theta, \phi)$ that is a function of position around the source (a glowworm, for example), write an expression for the total light output and the current output from a detector with a sensitivity of k in A/lm placed a radius of r from the source. Suppose the maximum luminous intensity of $I_0 = 0.85$ cd occurs directly above the source, what is the maximum current obtained from the detector assuming a sensitivity of $k = 12$ mA/lm with the detector at a distance of $r = 0.5$ m and having a detection surface of area $A = 1$ cm² (cm² not m²)?

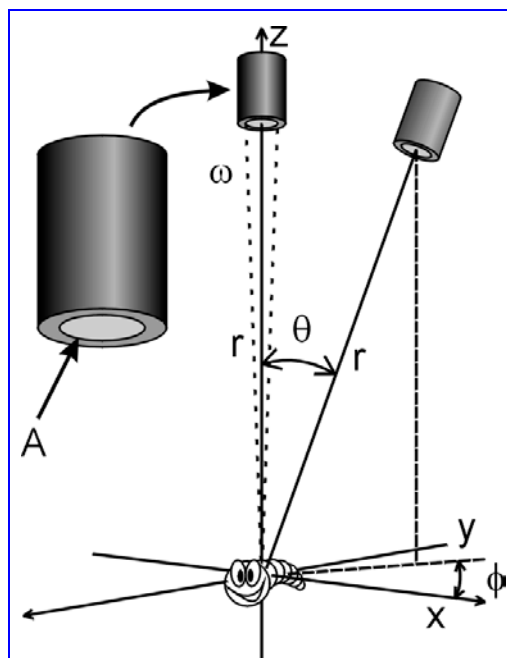
Suppose that the glowworm produces light in all directions. That light can be described by the luminous intensity as a function of orientation around the source or glowworm $I(\theta, \phi)$. The total light output (total luminous flux) is the integration of the luminous intensity over the spherical solid angle

$$\Phi_T = \oint I(\theta, \phi) \sin\theta d\theta d\phi, \quad (1)$$

but without knowing the exact form of I , we cannot perform the integration, of course. Here, $d\omega = \sin\theta d\theta d\phi$ is the element of solid angle in spherical coordinates. The amount of light entering the detector depends upon the area of the detector A and its distance from the source r .

We will assume that the detector is always oriented so that it is facing the source. If the detector were not facing the source, then we would have to correct for the misalignment by a cosine factor $\cos\beta$, where β is the angle between the axis of the detector (normal to the detector's surface) and the radius vector locating the position of the center of the face of the detector. For this problem we will assume that $\beta = 0$, i.e., the detector is always facing the source. The solid angle of the detector from the position of the source is $\omega = A/r^2$. The luminous flux entering the detector is simply

$$\Phi(\theta, \phi) = I\omega = I(\theta, \phi)A/r^2. \quad (2)$$





This light is converted to current J by the detector according to the relation $J = k\Phi$. Putting this altogether, the current output of the detector is

$$J(\theta, \phi) = k\Phi(\theta, \phi) = kI(\theta, \phi) A / r^2. \quad (3)$$

Thus, at the $\theta = 0$ position where $I(0,0) = I_0 = 0.85$ cd, given that $k = 12$ mA/lm, the luminous flux entering the detector of area $A = 1$ cm² ($= 0.0001$ m²) positioned at $r = 0.5$ m (solid angle $\omega = 0.0004$ sr) is $\Phi = I_0 \omega = I_0 A / r^2 = 3.4 \times 10^{-4}$ lm. The output of the detector would then be $J = k\Phi = 4.1$ μ A.

B6 PROPERTIES OF A LAMBERTIAN SURFACE

Abstract: A diffuse surface that has the same luminance when viewed from any direction independent of the direction of illumination for a constant illuminance is a Lambertian surface.

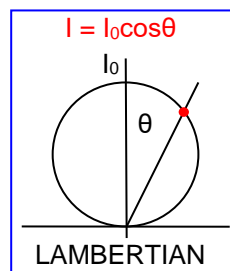
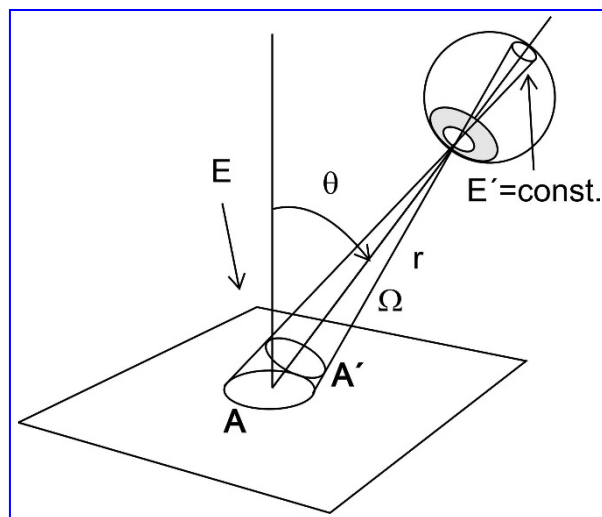
The luminous intensity from a small area A is $I = I_0 \cos \theta$, where θ is the angle from the perpendicular (or normal) of the surface and I_0 is the luminous intensity in the perpendicular direction. Also, given that the surface reflectance is ρ , we show that the luminance of a Lambertian surface is related to its illuminance by $L = \rho E / \pi$.

A Lambertian surface is one that will have the same luminance no matter from what angle the surface is observed. Many surfaces are quasi-Lambertian, flat (matte) paint, copy paper, etc. Consider looking at a small area on an extended surface. A simple way to obtain the desired result is to note that if the surface has the same luminance for any angle, then as our observation angle from the normal increases then we are looking at an extended or projected area within the same solid angle of view; and that area increases by $1/\cos \theta$. If the luminance is the same for any angle, as the observed area increases with larger angle from the perpendicular, the luminous intensity must decrease by $\cos \theta$ or $I = I_0 \cos \theta$, where I_0 is the perpendicular value.

If that is confusing, let's look at it in greater detail—even more confusing. Refer to the figure. For the view to remain the same really means that the area viewed by the eye is such that the solid angle it subtends remains constant. That is, if we say the eye sees the same something in all directions, we generally mean that the eye evaluates that something over a fixed solid angle. Thus $\Omega = \text{constant} = A'/r^2$. Here A' is the area perpendicular to the viewing direction (the apparent area) at angle θ and is related to actual area viewed on the surface via $A = A'/\cos \theta$. That is, when $\theta = 0$, the perpendicular direction, the area of the surface A is the same as the apparent area A' . The luminance is related to the luminous intensity by $I = LA \cos \theta = LA'$, or, since the luminance is constant $L = I/A' = \text{constant}$. (This is a long-distance approximation, see § B3.) Solving for the luminous intensity and expressing the area A in terms of the constant area A' we obtain $I = LA' = LA \cos \theta$. However, note that the quantity LA is the luminous intensity for $\theta = 0$, or $I_0 = LA$. Putting this together, we have the classic expression for the luminous intensity for a Lambertian emitter in terms of the luminous intensity normal to the surface I_0

$$I = I_0 \cos \theta, \quad [\text{LAMBERTIAN}]. \quad (1)$$

We can now define **luminance** another way: luminance L is the luminous intensity dI from a surface element dA in a given direction, per unit area of the element projected on a plane perpendicular to that given direction as given by $L = dI / (dA \cos \theta)$ where θ is the angle of the viewing direction. The $\cos \theta$ means that when you view the same surface element at an angle θ , its area looks smaller by a factor of $\cos \theta$. Assuming that the surface is uniform, the luminous intensity dI increases proportionally as dA increases, but the luminance L is constant and independent of dA . Also, if the surface is Lambertian, the luminous intensity I decreases by a factor of $\cos \theta$ as the viewing angle increases, but the luminance L is constant and independent of the viewing angle.





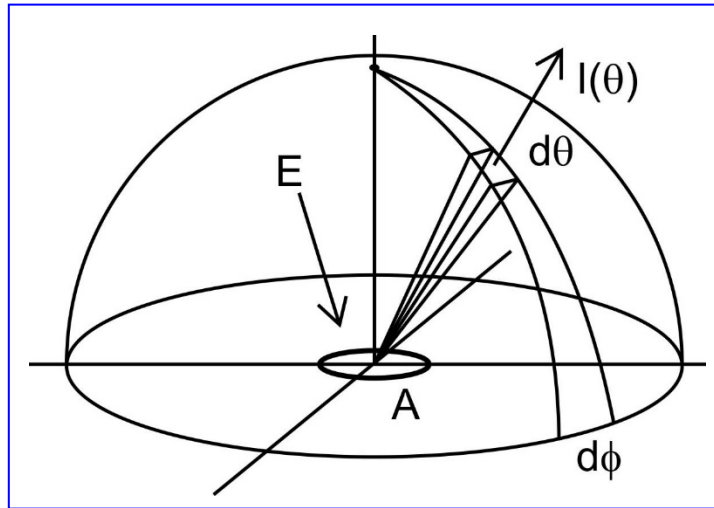
Reflection: Now, consider a reflecting diffuse surface (not an emitting surface) having area A . Let's assume that the fraction of the light reflected from the surface is ρ , known as the reflectance (often subscripted with a “d” for diffuse). Given an illuminance E lighting the surface we want to determine the luminance of the surface. The amount of luminous flux hitting the surface is $\Phi = EA$. The amount of flux leaving the surface is $\Phi' = \rho \Phi = \rho EA$, and must be equal to the integration of the luminous intensity over the hemispherical surface above the area A :

$$\Phi' = \rho \Phi = \rho EA = \iint I(\theta) d\omega = I_0 \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta \cos \theta \sin \theta = 2\pi LA \int_0^1 u du = \pi LA, \quad (2)$$

where $d\omega = \sin \theta d\theta d\phi$ is the element of solid angle. Solving for the luminance we obtain the relation between the luminance and the illuminance for a diffuse Lambertian reflector:

$$L = \frac{\rho}{\pi} E = qE, \quad (3)$$

where $q = \rho/\pi$ is called the luminance coefficient.





B7 UNIFORM COLLIMATED FLASHLIGHT

Problem: A Lambertian disk of reflectance $\rho = 0.95$ having a diameter of $d = 20$ mm is illuminated with a uniform collimated (parallel rays) beam of light of diameter $D = 50$ mm from a (very special) flashlight. The output of the flashlight is $\Phi = 100$ lm, and all the light is contained within the beam. What is the luminous exitance M of the flashlight, what is the illuminance E on the disk, and what is the luminous intensity reflected from the disk (assuming that the disk is small compared to the observation distance)? Given a photopic detector (like a photodiode with a photopic filter) having a diameter $\delta = 5$ mm and sensitivity of $k = 6$ A/lm, what is the output J of the detector in amperes (A) as a function of angle from the perpendicular θ with the detector placed at a distance $r = 300$ mm and with the detector always facing the disk (its axis passes through the center of the disk)? Calculate the output for $\theta = 30^\circ$. How would the output of the detector change if it is tilted an angle $\phi = 60^\circ$ from directly facing the disk?

The luminous exitance M is simply the luminous flux $\Phi = 100$ lm divided by the area

$$A = \pi D^2/4 = 0.00196 \text{ m}^2 \quad (1)$$

($D = 0.05$ m) of the aperture of the flashlight, or

$$M = \frac{\Phi}{A} = \frac{4\Phi}{\pi D^2} = 50930 \text{ lm/m}^2. \quad (2)$$

Because the beam is collimated it remains the same diameter along its path (hard or impossible to do in reality, but some spotlights come fairly close) and has a uniform cross-section. Therefore, the illuminance on the white disk is the same as the luminous exitance:

$$E = \Phi/A = 50930 \text{ lx}. \quad (3)$$

(Note that whereas illuminance is in lx, luminous exitance is expressed in lm/m².) The luminance L of a Lambertian object normally illuminated with illuminance E (see § B3 Luminance of a Uniform Area) is given by

$$L = qE = \frac{\rho}{\pi} E = 15400 \text{ cd/m}^2. \quad (4)$$

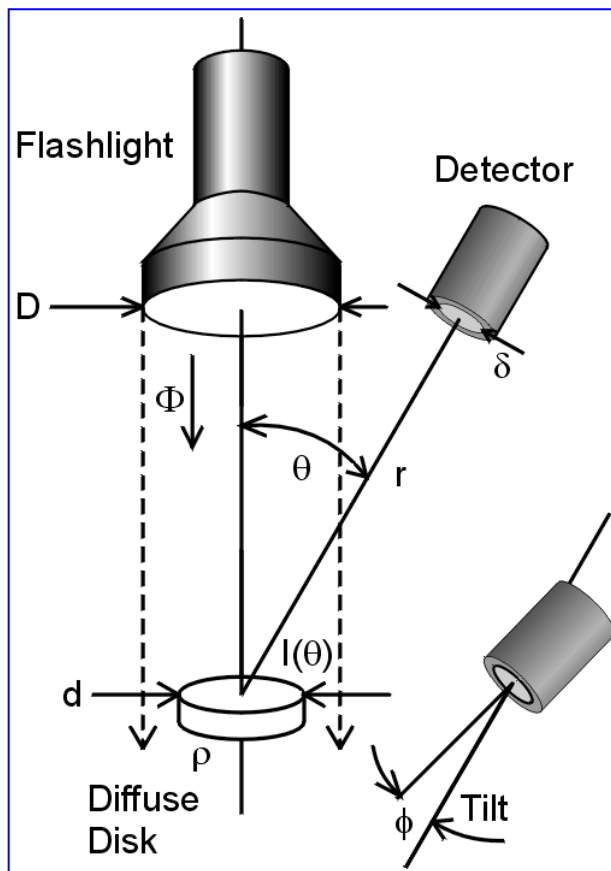
The luminous intensity I from a Lambertian reflector (§ B6) having a luminance L and area $a = \pi d^2/4 = 3.14 \times 10^{-4} \text{ m}^2$ is given by

$$I = I(\theta) = I_0 \cos \theta = aL \cos \theta, \quad (5)$$

provided that the distance r at which I is observed is large compared to the diameter of the disk d , that is, $r \gg d$. (See § B10 for an exact calculation of the illuminance from a Lambertian emitter.) Here the maximum luminous intensity I_0 along the normal of the disk is $I_0 = La = 4.838 \text{ cd}$.

This light enters through the aperture (diameter $\delta = 0.005$ m, area $\alpha = \pi \delta^2/4 = 1.963 \times 10^{-5} \text{ m}^2$) of the detector placed a distance r away. Since the output of the detector in amps ($J = k\Phi$, $k = 6$ A/lm) depends upon the luminous flux entering the aperture, which we will call F to avoid confusion with Φ , we need to determine F from the luminous intensity I . We know the solid angle of the detector as viewed from the center of the disk is given by

$$\omega = \frac{\alpha}{r^2} = \frac{\pi \delta^2}{4r^2} = 2.182 \times 10^{-4} \text{ sr}. \quad (6)$$





The luminous flux entering the detector is the product of the luminous intensity and the solid angle

$$F = I(\theta)\omega = La\omega\cos\theta = \frac{\rho}{\pi}\Phi\frac{d^2}{D^2}\alpha\frac{\cos\theta}{r^2} = F_0\cos\theta, \quad (7)$$

where $F_0 = I_0\omega = 1.056 \times 10^{-3}$ lm is the maximum flux at the normal position if the detector could be placed there without interfering with the illumination of the disk. The output of the detector is simply

$$J = kF = J_0\cos\theta, \quad (8)$$

where $J_0 = 6.33$ mA is the limiting current possible for this configuration. For $\theta = 30^\circ$ we obtain $F = 9.141 \times 10^{-4}$ lm and $J = 5.48$ mA.

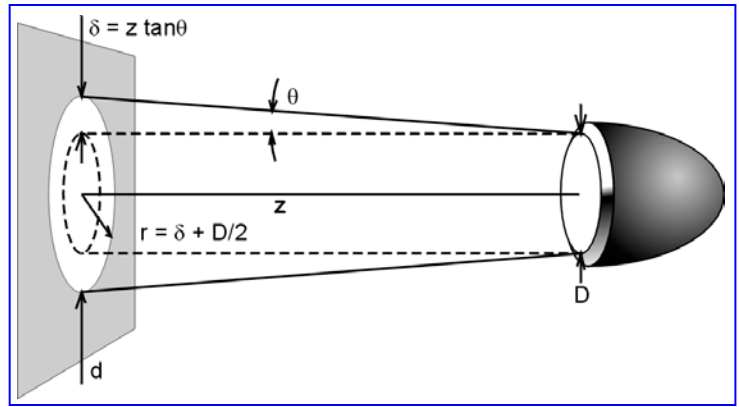
If we were to turn the detector so that the normal of the detector surface makes a tilt angle of $\phi = 60^\circ$ from the line from the center of the disk to the center of the detector, we would simply need another cosine term. The signal would then be

$$J = J_0\cos\theta\cos\phi = 2.74 \text{ mA}, \quad (9)$$

using $\theta = 30^\circ$ and $\phi = 60^\circ$.

B8 HEADLIGHT (DIVERGENT UNIFORM FLASHLIGHT)

Problem: Given a uniform divergent flashlight—a motorcycle headlight—with luminous flux $\Phi = 250$ lm, diameter $D = 100$ mm, and diverging at an angle of $\theta = 2^\circ$ in all directions from its surface perpendicular, calculate the illuminance as a function of distance z from the surface of the headlight, then express the luminance as a function of distance of the headlight from a white wall with diffuse (Lambertian) reflectance of $\rho = 0.91$ ($z = 0$ when the headlight is touching the wall). Now, suppose you are riding your motorcycle at night, and you are just able to see a white sign (like our wall) at a distance of $z_1 = 100$ m. You would like to be able to see further than that. You see an advertisement for a special headlight that is twice as bright as your stock headlight, and they claim that you can see twice as far as a consequence. Is that claim true for normal photopic vision (see § B9)?



The light is spread uniformly over an area $a = \pi r^2$ on the wall, where the radius $r = \delta + D/2$, and $\delta = z \tan\theta$ is the extension of the radius of the beam from the original radius of the beam ($D/2$) as we move out along z . Specifically, the area of the beam spot on the wall is

$$a = \pi \left(\frac{D}{2} + z \tan\theta \right)^2. \quad (1)$$

The illuminance is simply the luminous flux spread over the beam spot on the wall

$$E = \frac{\Phi}{a} = \frac{4\Phi}{\pi(D + 2z \tan\theta)^2}. \quad (2)$$

Since the wall is a Lambertian surface the luminance is given by (§B6)

$$L = \frac{\rho}{\pi} E = \frac{4\rho\Phi}{\pi^2(D + 2z \tan\theta)^2}. \quad (3)$$

If you were a small bug on the headlight and the headlight were placed against the wall so that $z = 0$, the illuminance would be a maximum of



$$E_{\max} = \frac{\Phi}{\pi(D/2)^2} = 3183 \text{ lx} = M \text{ [in lm/m}^2\text{]} \text{ (for } z = 0), \quad (5)$$

which is the luminous exitance M of the headlight. The associated maximum luminance would be

$$L_{\max} = \frac{\rho\Phi}{\pi^2(D/2)^2} = 9220 \text{ cd/m}^2 \text{ (for } z = 0). \quad (6)$$

We can solve for z in the exact expression for luminance (Eq. 3) to get

$$z = \frac{1}{\tan \theta} \left(\sqrt{\frac{\rho\Phi}{\pi^2 L}} - \frac{D}{2} \right), \quad (7)$$

and use this to determine the new distance with the improved light.

To examine the claims of the advertisement, we could use the exact equations (Eqs. 3, 7), but we note that for long distances $z \gg D$ approximate equations will be sufficient:

$$L \cong \frac{\rho\Phi}{(\pi z \tan \theta)^2}, \quad z \cong \frac{1}{\pi \tan \theta} \sqrt{\frac{\rho\Phi}{L}}, \text{ for } z \gg D. \quad (8)$$

(Note the $1/z^2$ behavior in the luminance.) For $z_1 = 100$ m the luminance of a white object like the wall would be $L_1 = 1.89 \text{ cd/m}^2$. We want to determine the new distance z_2 at which the luminance will be the same $L_2 = L_1$ for a headlight with twice the output, $\Phi_2 = 2\Phi_1 = 500 \text{ lm}$. Using Eq. 8 we find $z_2 = 141$ m. Thus, the claim is incorrect, assuming that we are using normal photopic vision in the non-linear regions of the eye response—how well that assumption holds is not the purpose of this discussion. Twice the output would appear to only give you a 41 % increase in the usable distance—at least this calculation raises a caution flag regarding such claims. This is obvious using the approximate Eq. (8) and writing the ratios

$$\frac{L_2}{L_1} = \frac{\Phi_2 z_1^2}{\Phi_1 z_2^2}, \quad \frac{z_2}{z_1} = \sqrt{\frac{\Phi_2 L_1}{\Phi_1 L_2}}, \quad (8)$$

in general. Using $L_1 = L_2$ and $\Phi_2 = 2\Phi_1$, then $z_2/z_1 = \sqrt{2}$, as we obtained above.

The above discussion assumes photopic nonlinear vision properties. How true this is for vision from headlights needs to be tested for far-field illumination while standing in the near-field illumination of the lamp. This is not to say that all the vision associated with driving a vehicle is nonlinear. In fact, there is an easy way to see the linear properties of your vision system: In daylight, your deeply tinted windows on your car don't appear to darken the outside very much, but at night you can hardly see out the back of the car to back up with those same windows! The reason for the change is that at night in the low light levels when looking out the back of your car you are in a more linear regime of your vision than when looking at the area illuminated by your headlights.

B9 NONLINEAR RESPONSE OF EYE

The human visual system is highly nonlinear, and this nonlinearity involves spatio-temporal properties of the light stimulus as well as adaptation levels of the eye and chromatic dependencies. However, standards bodies and display technologies adopt the following rule of thumb: “Roughly speaking, perceived lightness is the cube root of luminance.” (C. A. Poynton, SMPTE Journal, December 1993, p. 1101). This law appears in the uniform color spaces such as CIELUV and CIELAB (see § B1).

The cube-root law is the result of experiments such as the following: An observer is given a black and a white chip and asked to select a gray chip that is halfway between the two in lightness (on a particular background, and under a given illuminant). Then, the observer is asked to halve the black-gray and gray-white intervals by the same procedure. Continuing this process yields a series of chips that are subjectively equally spaced and are assigned numerically equal increments of lightness. The measured luminances of these chips complete the lightness-luminance relationship, which has the appearance of a power function, most characteristically the cube-root function. What this means is that if the luminance L_1 of one object appears to the eye to be half the luminance of another object L_2 , then their luminance ratio is approximately 8:1;

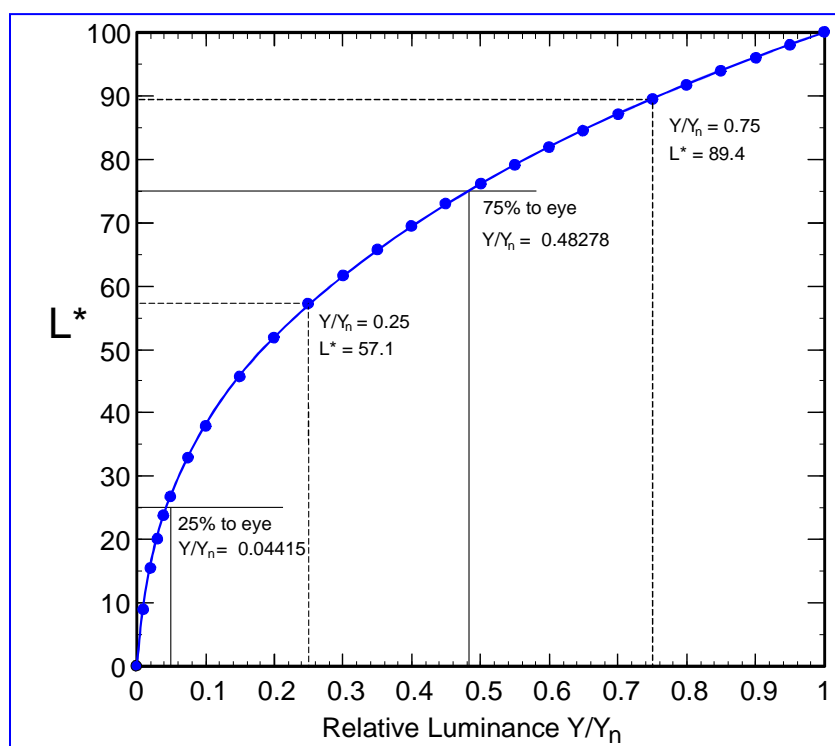
$\sqrt[3]{L_2/L_1} = 2$, so then $L_2/L_1 = 8$. Thus, if we have a computer display that has a luminance of 100 cd/m^2 and want a new display to appear twice as bright, then we would need the new display to have a luminance of 800 cd/m^2 .



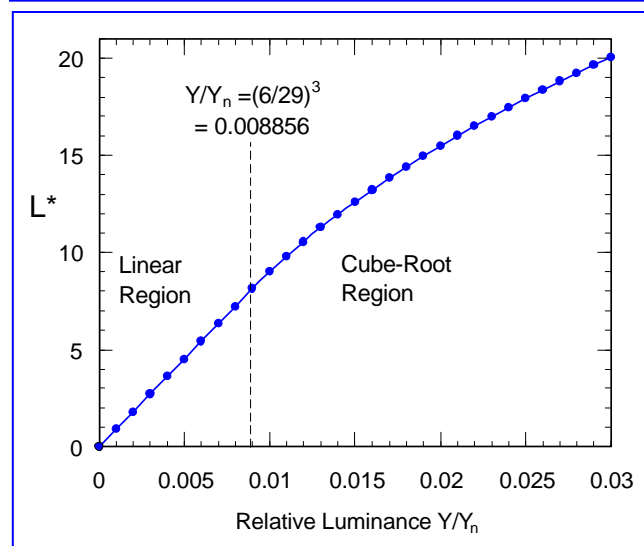
Many modern displays are capable of a virtually continuous luminance range from black to white, and low luminance values are readily available and observable. Therefore, the good eye model to use to deal with the entire display luminance range is L^* in the CIELUV and CIELAB color spaces (L^* is the same for both spaces)—see § B1 Radiometer, Photometry and Colorimetry for details. Given a luminance Y and white luminance of Y_w , the relationship between L^* and the ratio Y/Y_w (with the use of older numerical expressions for L^*):

$$L^* = \begin{cases} 116 \left(\frac{Y}{Y_w} \right)^{1/3} - 16, & \text{for } \frac{Y}{Y_w} \geq 0.008856 \\ 903.3 \frac{Y}{Y_w}, & \text{for } \frac{Y}{Y_w} \leq 0.008856 \end{cases}$$

$$\frac{Y}{Y_w} = \left(\frac{L^* + 16}{116} \right)^3, \text{ but } \frac{Y}{Y_w} = \frac{L^*}{903.3}, \text{ for } L^* < 8$$



Be careful not to confuse the linear luminance scale with the nonlinear eye response characterized by L^* . For example, a pixel may be considered stuck on if its luminance is always greater than 75 % of white and stuck off if its luminance is always less than 25 % of white. Don't confuse this with what the eye sees. A pixel with 25 % white luminance appears to the eye to be 57 % of the white luminance; similarly, 75 %, appears to the eye as 89 %. If we wanted to judge the pixel based on appearance thresholds of 25 % and 75 % of white, we would use the luminance-of-white criteria of 4.415 % and 48.28 %.





B10 $E(z)$ FROM EXIT PORT OF INTEGRATING SPHERE

Problem: Given a $D = 50$ mm exit port of an integrating sphere with uniform luminance of $L = 5000$ cd/m², determine the illuminance as a function of distance $E(z)$ from the exit port along the axis of the exit port. At what distance can the exit port be treated as a point source of light with less than 1 % error?

We calculate the contribution dE to the total illuminance from an element of area dA in the plane of the exit port. We consider an area a at position z from the center of the exit port. The luminous intensity from dA is

$$dI = L dA \cos \theta, \quad (1)$$

where we assume that the luminance L arises from a Lambertian surface and is therefore constant for all directions—see § B3, Eq (4). The area a subtends a solid angle of

$$\omega = (a/r^2) \cos \theta \quad (2)$$

from the viewpoint of the area element dA . Here the cosine term comes from the fact that the area a is also tilted with respect to the line between dA and a . Not only is the emission from dA decreased by the cosine term, but the amount of light through a is also decreased by the cosine term because the area a is not facing the element dA (the surface normal of a is not pointing at dA). The area element dA is the product the arc arising from $d\phi$ ($d\phi$ times the radius in the plane of the exit port $r \sin \theta$) and the arc arising from $d\theta$ (since we are confined to the plane of the exit port, the radial arc length $rd\theta$ must be extended to $rd\theta/\cos \theta$), or

$$dA = r^2 (\sin \theta / \cos \theta) d\theta d\phi. \quad (3)$$

The amount of flux $d\Phi$ passing through a from dA is then

$$d\Phi = \omega dI = L dA \frac{a}{r^2} \cos^2 \theta, \quad (4)$$

and the illuminance contribution is

$$dE = \frac{d\Phi}{a} = L \sin \theta \cos \theta d\theta d\phi, \quad (5)$$

where we have used the expression for the element of area dA . Integrating this over the exit port gives the illuminance as a function of z . Note that ϕ runs from 0 to 2π and θ runs from 0 to θ_{\max} , where θ_{\max} is given by

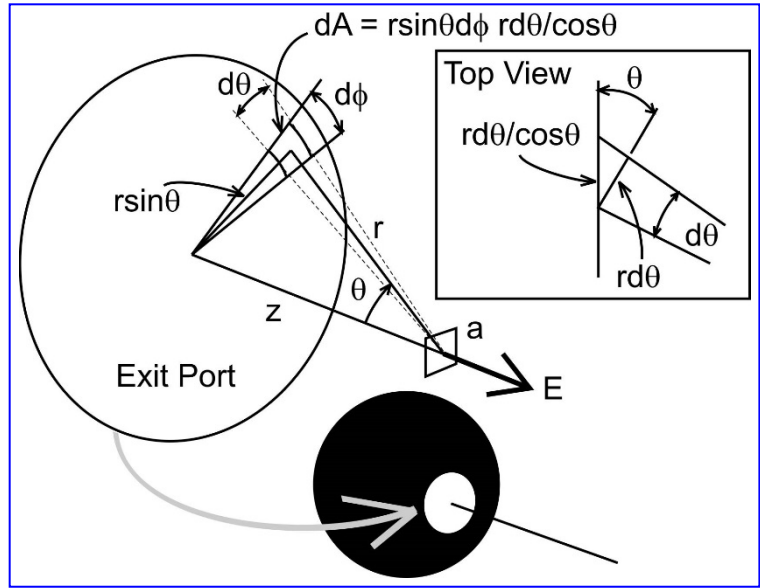
$$\sin \theta_{\max} = \frac{R}{\sqrt{R^2 + z^2}}, \quad (6)$$

and where R is the radius of the exit port, $R = D/2 = 25$ mm. The illuminance is

$$E(z) = \int_0^{2\pi} d\phi \int_0^{\theta_{\max}} L \sin \theta \cos \theta d\theta = 2\pi L \int_0^{\sin \theta_{\max}} u du = 2\pi L (\sin^2 \theta_{\max}) / 2, \quad (7)$$

(using the substitution $u = \sin \theta$) or

$$E(z) = \frac{\pi R^2 L}{z^2 + R^2} = \frac{AL}{z^2 + R^2} = \frac{\pi L}{1 + (z/R)^2} = \pi L \sin^2 \theta_{\max}. \quad (8)$$





Let's examine the values for $z = 0$ and $z \gg R$ and compare:

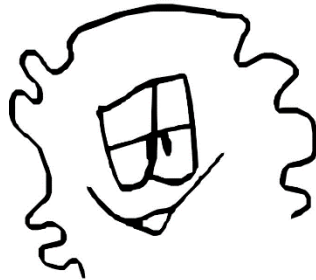
$$E(z) = \begin{cases} \pi L, & \text{for } z = 0 \\ \frac{LA}{z^2}, & \text{for } z \gg R \\ \frac{LA}{z^2 + R^2}, & \text{for all } z \text{ and all } R \end{cases} \quad \begin{cases} = I_0 / z^2, \text{ using } I_0 = LA \\ \text{(Treats exit port as point source [} A = \pi R^2 \text{])}. \\ = L\Omega, \text{ using } \Omega = A / z^2 = \pi R^2 / z^2 \\ \Omega \text{ is solid angle of exit port from } z \end{cases} \quad (9)$$

$\{ = \pi L \sin^2 \theta_{\max} \}$

Here A is the total area of the exit port, and Ω is the solid angle of the exit port as viewed from the z -position. The result for $z = 0$ is what we get in § B15 where we derive the relationship between the illuminance and luminance of the walls of an integrating sphere. The large- z approximation essentially treats the exit port as a point source with a $1/z^2$ dependence. Comparing the exact expression for the illuminance (Eq. 8) with the large- z expression (Eq. 9) amounts to comparing R^2/z^2 with $R^2/(R^2 + z^2)$. These two functions differ by slightly less than 1 % when $z = 10R = 5D$. Thus, we can use the simple forms in Eq. 9 for Lambertian emitters whenever we are more than five diameters away from the light source and be within 1 % of the exact result. Although we say that the last equation is good for all z and all R , in practice you will find that nonlinearities on the interior of the integrating sphere may start to affect the results as you get close to the integrating sphere in the range $z < 2D$ or even farther away than this.

A simpler way to obtain the result in Eq. 8 is to consider a spherical cap defined by the exit port where the cap extends inside the integrating sphere. The normal of each area element dA on the spherical cap points toward our observation point at z with luminance intensity of $dI = LdA/r^2$. The element of illuminance $dE = Ld\Omega$ simply integrates to $E(z) = \pi L \sin^2 \theta$.

THE NIT IS A DEPRECATED UNIT!



It's a good thing we can say "watt"! Imagine: "Please give me a package of four 60-kilogram-meter-squared-per-second-cubed bulbs."



Whut?!



Nobody can accuse them of being nit-pickers!



The pressure today is 102430 kilograms-per-second-squared-per-meter.



Here's one: "I'd like 20 4.7 micro-amps-squared-seconds-to-the-fourth-killograms-to-the-minus-one-meters-to-the-minus-two capacitors for my project."



B11 EXIT PORT ILLUMINATION OF A WALL

Problem: Given a $D = 50$ mm exit port of an integrating sphere with uniform luminance of $L = 5000$ cd/m², determine the radial distribution of the luminance on a Lambertian wall having a reflectance of $\rho = 0.75$ as a function of distance z from the exit port for large z compared to the exit port diameter ($z > 5D$). Assume the exit port surface is parallel to the wall. Essentially this is a calculation of $L(z, r)$ on the wall. What is the maximum wall luminance if $z = 1$ m? How would the problem change if instead of an integrating sphere we used a light bulb that produced a uniform luminous intensity I radially about its center.

Since the distance z is large we can use the results of the previous section and treat the exit port as a point source with the luminous intensity expressed by $I = LA \cos \theta$, where A is the area of the exit port,

$A = \pi D^2/4 = 0.00196$ m². Consider a small area a , a distance R from the center of the wall defined by the normal of the exit port. The distance from the exit port to a is $r = \sqrt{z^2 + R^2} = z / \cos \theta$, where the angle between the radius vector and the normal of the exit port is $\theta = \tan^{-1}(R/z)$, or $\tan \theta = R/z$, etc. The solid angle of that area a as viewed from the center of the exit port is $\Omega = (a/r^2) \cos \theta$, where the cosine factor arises from the tilt of a relative to the radius vector. The luminous flux through a is simply

$$\Phi = I\Omega = LA \frac{a}{r^2} \cos^2 \theta = aLA \frac{\cos^4 \theta}{z^2}, \quad (1)$$

where we have used the fact that $r = z/\cos \theta$. The illuminance on the wall $E = \Phi/a$ and the luminance of the Lambertian wall $L_w = \rho E/\pi$ are given by

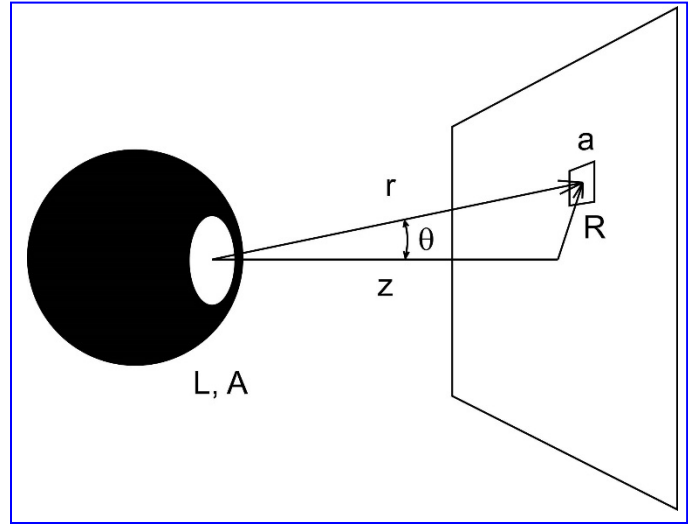
$$E = LA \frac{\cos^4 \theta}{z^2} = LA \frac{z^2}{(R^2 + z^2)^2}, \quad (2)$$

$$L_w = \frac{\rho}{\pi} LA \frac{\cos^4 \theta}{z^2} = \frac{\rho}{\pi} LA \frac{z^2}{(R^2 + z^2)^2}. \quad (3)$$

The fourth power of the cosine will appear again in § B13 with a very similar derivation. It is referred to as the \cos^4 illumination law or \cos^4 falloff. The maximum luminance occurs at $R = 0$. With a distance of $z = 1$ m the maximum luminance is given by $L_{\max} = \rho LA / \pi z^2 = 2.34$ cd/m².

This problem has been treated as if the apparatus were in a very large room with totally black walls and with equipment that doesn't reflect any light (an impossible situation). If you were to try this experiment and measure the luminance of object such as a white disk (instead of a wall), you would discover how much reflections from nearby objects—even black objects—will add to the measured luminance of the disk over the calculated luminance (see § B16).

Now suppose we have a lamp having a radially uniform luminous intensity of I . The luminous flux upon a is $\Phi = I\Omega$, whereas in the above, $\Omega = (a/r^2) \cos \theta = (a/z^2) \cos^3 \theta$. The illuminance is $E = \Phi/a = (I/z^2) \cos^3 \theta$. Note that the cosine term accounting for the tilt of a is already in the solid angle Ω . If our perfect lamp has a luminous flux output of Φ_0 over the entire spherical region surrounding it (4π sr), then $I = \Phi_0/4\pi$. The difference between using the integrating sphere vs. the lamp is that the luminous intensity from the exit port of the integrating sphere is not constant (as it is with our perfect lamp), but goes down as $\cos \theta$, thus, introducing another cosine factor.





B12 INTEGRATING SPHERE INTERIOR — L & E

Problem: Given an integrating sphere of diameter $D = 150$ mm with an exit port diameter of $d = 50$ mm, suppose there is a light source which illuminates the interior of the sphere uniformly with a luminous flux of $\Phi_0 = 100$ lm. Determine the luminance L of the exit port when the walls have a diffuse reflectance of $\rho = 0.98$.

Let the area of the entire integrating sphere including the exit port be

$$S = 4\pi D^2/4 = 0.0707 \text{ m}^2. \quad (1)$$

Let the area of the exit port be

$$A = \pi d^2/4 = 0.00196 \text{ m}^2. \quad (2)$$

There are multiple reflections within the sphere. We will assume that the luminous flux

Φ_0 is inserted into the sphere perfectly (as if we had an infinitesimally small lamp near the center of the sphere). Initially the flux incident upon the walls provides an illuminance for the first reflection of $E_0 = \Phi_0/S$ which produces the first contribution to the luminance $L_1 = \rho E_0/\pi = \rho \Phi_0/\pi S$. At the first reflection the returned flux available for further reflections Φ_1 is reduced from the incident flux by the reflectance ρ and the fact that the exit port eliminates a fraction of the light: $\Phi_1 = \rho \Phi_0(S - A)/S$. Historically, the factor $(S - A)/S$ is written as $(1 - f)$, where

$$f \equiv A/S \quad (3)$$

is the relative area of the exit port compared to the total area of the sphere. Thus, $\Phi_1 = \Phi_0 \rho(1 - f)$. The contribution to the illuminance is then $E_1 = \Phi_1/S$, and the contribution to the luminance for the second reflection will be

$L_2 = \rho E_1/\pi = \rho \Phi_1/\pi S = (\rho \Phi_0/\pi S) \rho(1 - f)$. The reflections continue:

$\Phi_2 = \Phi_1 \rho(1 - f) = (\rho \Phi_0/\pi S) \rho^2(1 - f)^2$, $E_2 = \Phi_2/S$, and $L_3 = \rho E_2/\pi = \rho \Phi_2/\pi S = (\rho \Phi_0/\pi S) \rho^2(1 - f)^2$.

The general terms are, for $n = 0$ to ∞ :

$$\begin{aligned} \Phi_n &= \Phi_0 \rho^n (1 - f)^n \\ L_{n+1} &= \frac{\rho \Phi_0}{\pi S} \rho^n (1 - f)^n \end{aligned} \quad (4)$$

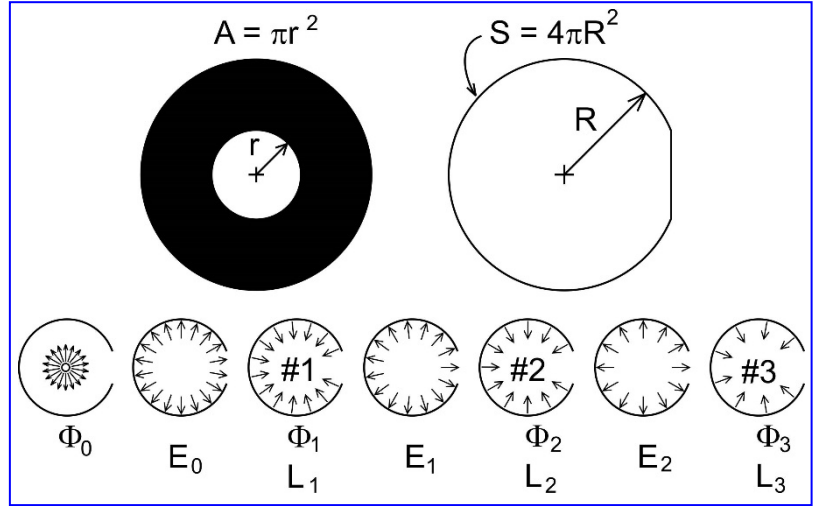
In performing the summations, we note that $1 + x + x^2 + x^3 + \dots = 1/(1 - x)$ for $x < 1$. The total luminous flux and total luminance are given by:

$$\begin{aligned} \Phi &= \Phi_0 + \Phi_1 + \Phi_2 + \dots = \frac{\Phi_0}{1 - \rho(1 - f)} \\ L &= L_1 + L_2 + L_3 + \dots = \frac{\Phi_0}{\pi S} \frac{\rho}{1 - \rho(1 - f)} \end{aligned} \quad (5)$$

If we had just calculated the total luminous flux inside the integrating sphere, we could have written down the luminance directly:

$$L = \frac{\rho}{\pi} E = \frac{\rho \Phi}{\pi S}, \quad (6)$$

using $E = \Phi/S$. Here Φ is given by the expression in Eq. 5. For our numbers $f = 0.02778$, the luminous flux inside the sphere is $\Phi = 2118$ lm (compare that with the input flux of $\Phi_0 = 100$ lm), and the luminance is $L = 9345$ cd/m².

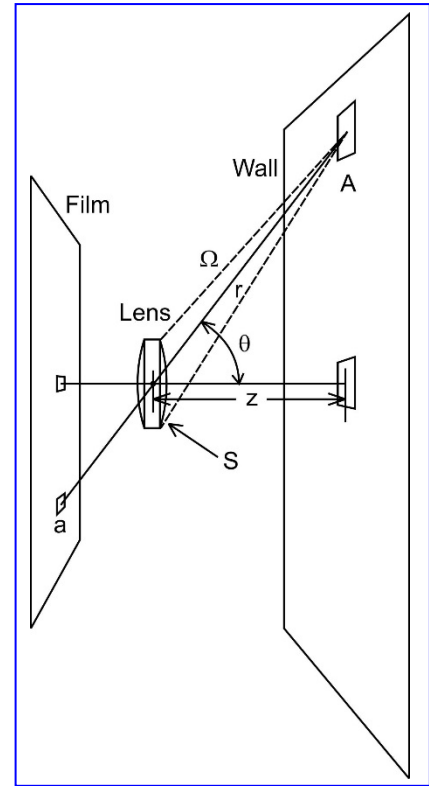




B13 LENS $\cos^4(\theta)$ VIGNETTE

Problem: Lenses will often not provide uniform illumination over a wide angle of view. We show how a simple lens (or aperture or pin hole) will provide a $\cos^4\theta$ fall-off in transmitted luminous flux as θ increases from the axis of the lens system when the lens is viewing a surface of infinite extent that has a uniform luminance of L .

This is remarkably easy to understand. Given two planes parallel to each other—as with a camera viewing a wall. One is the object plane (infinite wall) and the other is the image plane (the film). Any area on the object plane A is focused to a corresponding area in the image plane a by a lens with area S positioned a distance z away from the wall. The wall (object plane) is assumed to be a Lambertian emitter. Therefore, this area A at angle θ from the optical axis (normal to the planes) produces a luminous intensity of $I = LA \cos \theta$ in the direction of the lens. The distance between the lens and area A is $r = z / \cos \theta$. This light from A hits the lens at an angle θ , so the solid angle from A to the lens is $\Omega = S \cos \theta / r^2 = (S/z^2) \cos^3 \theta$. The luminous flux through the lens is $\Phi = I \Omega = (LAS/z^2) \cos^4 \theta$. This is the light that hits the image area a , the image of A . Another cosine term does not enter into the resulting illuminance on the image plane $E = \Phi/a$; in other words all the flux Φ coming from A through the lens hits the image area a . (This is not the case where we have a well-defined beam of light of a certain diameter hitting a surface at an angle so that the diameter of the beam spot on the surface increases [the spot becomes a more eccentric ellipse] as the angle increases. In such a case, the light is spread over an increasingly larger area, and the illuminance is thereby reduced by a cosine term.) Thus, two cosine terms enter because the area A is tilted to the line of sight as is the lens (one cosine comes from the Lambertian emission of light and the other from the tilt of the lens), and two cosine terms enter in because of the $1/r^2$ nature of the illumination. Another way to look at this is: Three cosine terms arise from the solid angle of the lens (the $1/r^2$ nature and the tilt of the lens with respect to the viewing direction along r), and one cosine term comes from the Lambertian nature of the emitting surface. Although we discussed a lens here, the same result is true for an aperture and a pin hole.

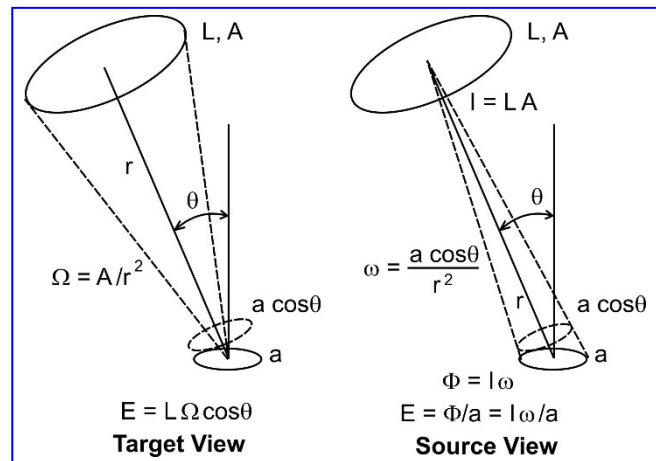


B14 ILLUMINANCE FROM LUMINANCE

Abstract: Consider a uniform luminance source of diameter D illuminating a target surface at an arbitrary angle θ , compare the view from the target with the view from the source, that is, compare how the target is illuminated with an illuminance from the source with how the source provides a luminous intensity for the target.

As you play with these problems, you will find that there are two ways to look at a distant light source: from the source's viewpoint or from the target's viewpoint. Consider a Lambertian emitter of area A and luminance L a distance r away from and at an angle θ from the normal of a target having area a . Suppose $r \gg \sqrt{A}$ and also $r \gg \sqrt{a}$, so that we can use our approximate in § B10 $E(z)$ from Exit Port of Integrating Sphere, where we treat distant sources as point sources. Assume that the source disk is facing the target (the normal of the disk's center intersects the center of the target disk a).

Source Viewpoint: In the source view, the luminous intensity from the source $I = LA$, is aimed at a disk tilted at an angle of θ . From the viewpoint of the source, we are concerned about the solid angle of the target as viewed from the source. The solid angle of the target is therefore $\omega = a \cos \theta / r^2$, and the luminous flux hitting the target is





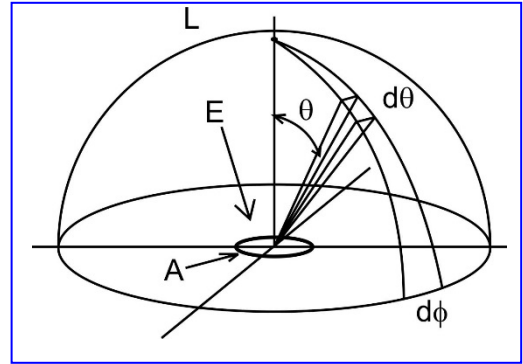
simply $\Phi = I\omega$. The illuminance is $E = \Phi/a$ or $E = L A \cos \theta / r^2$. Note that the quantity A/r^2 is the solid angle of the source from the viewpoint of the detector $\Omega = A/r^2$. Thus, we can also write the illuminance as $E = L \Omega \cos \theta$, where the cosine term accounts for the tilt of the target relative to the normal of the source.

Target Viewpoint: This formulation $E = L \Omega \cos \theta$ appears like we are treating the source as providing an incident illuminance of $E_0 = L \Omega$ that arises from a luminance L . The cosine term accounts for the foreshortening of a from the off-normal position of the source. From the viewpoint of the target, we are concerned about the solid angle of the source as viewed from the target.

B15 ILLUMINANCE INSIDE AN INTEGRATING SPHERE

Problem: Given an integrating sphere of diameter $D = 150$ mm that does not have an exit port, suppose there is a light source that (coupled with the high diffuse reflectance of the interior surface) illuminates the interior of the sphere uniformly so that the luminance L of the surface of the integrating sphere is 2000 cd/m^2 . What is the illuminance on the walls, and what is the illuminance on a small surface placed at the center of the integrating sphere?

Consider a disk at the center of a perfect integrating sphere having a wall (interior surface) luminance of L . We assume that the wall surfaces are Lambertian with reflectance ρ . The illuminance on the walls E_s is then related to the luminance by $L = \rho E_s / \pi$, or $E_s = \pi L / \rho$. The only parts of the walls that contribute to the illuminance of our disk are in the hemisphere above the disk. Define a spherical coordinate system (θ, ϕ) with the polar axis aligned with the normal of the disk (and at the center of the sphere). From the previous problem we can consider the luminance L from a small element of the surface giving rise to an illuminance $dE = L d\omega \cos \theta$, where $d\omega = \sin \theta d\theta d\phi$ is the solid angle of the surface element from the center of the sphere, and the cosine term accounts for the off-axis position relative to the disk. The total illuminance upon the disk is given by the integration of the elements of illuminance:



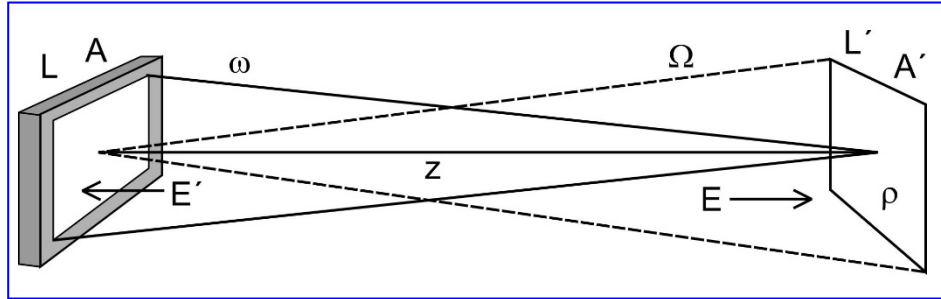
$$E = \int dE = L \int_0^{2\pi} d\phi \int_0^{\pi/2} \cos \theta \sin \theta d\theta = 2\pi L \int_0^1 u du = \pi L,$$

where the substitution $u = \sin \theta$ was used. The illuminance on a surface centered in an integrating sphere is $E = \pi L$ whereas the illuminance on the surface of the interior walls is slightly larger $E_s = \pi L / \rho$ by the inverse of the reflectance. Why the difference? The difference comes from the fact that the illuminance on the sphere wall includes the direct illumination from the source, whereas the sample does not receive that illuminance. If you were to measure the illuminance E and luminance L on an area of the sphere wall shadowed by a baffle, then you would obtain $E = \pi L$.



B16 REFLECTION FROM ROOM WALLS ONTO SCREEN

Problem: What can happen to your measurements when you are wearing a white shirt and standing inappropriately near the screen albeit in a darkroom? Suppose a display has a surface area $A = 300 \text{ mm} \times 225 \text{ mm}$ and exhibits a uniform luminance of $L = 100 \text{ cd/m}^2$. A card of area $A' = 300 \text{ mm} \times 300 \text{ mm} = 0.09 \text{ m}^2$, luminance factor $\rho_d = 0.90$, and placed a distance $z = 1.2 \text{ m}$ away in front of the display. What is the approximate illuminance back on the display surface that is provided by the reflected light from the board? If

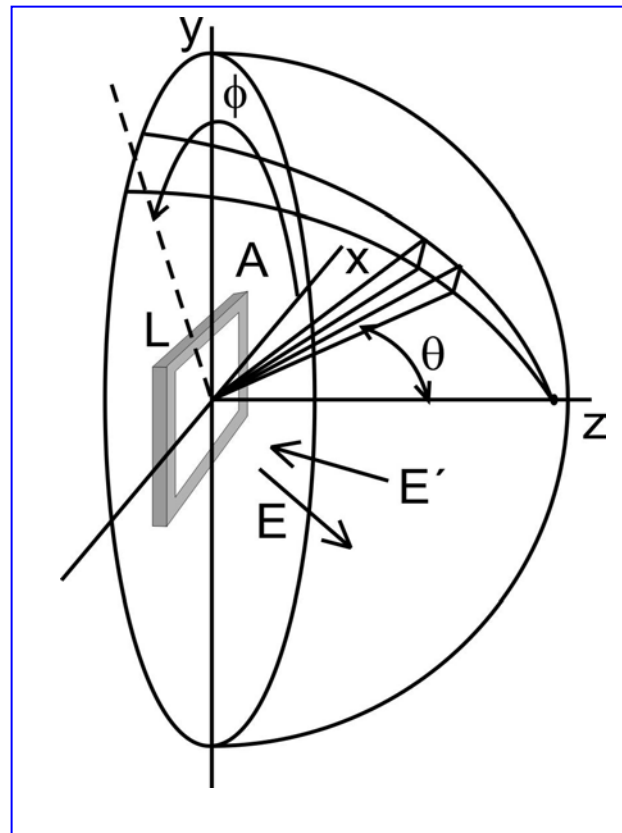


the screen surface has a specular reflectance of $\rho_s = 0.11$ for this configuration, what is the luminance corruption of a small black square placed on the white screen? (This shows the danger of reflections from your clothes and nearby objects, and how they might influence the measurements.) Now, suppose that the walls in the room are spherical, centered on the display, with radius $r = 3 \text{ m}$, and having an average luminance factor of $\rho_d = 0.18$, what is the illuminance reflected back at the display. This provides a means of estimating the contribution of the environment to stray light hitting the screen that originates from the screen. Typical landscape scenes, as photographers know, reflect about 18 % of the light incident upon them.

We are making an approximation to determine how much a person standing in the vicinity of the screen wearing a white shirt will affect measurements of small black areas. Since an approximate value is called for in the first part of the problem, we will use the long-distance approximations developed in § B10 to avoid the complicated integrations that a full treatment would require. The luminous intensity from the display is $I = LA \cos \theta$, where θ is the angle from the normal of the display. Since we assume the card is centered at and perpendicular to the normal of the display, we can use $I = LA$. With $A = 6.750 \times 10^{-2} \text{ m}^2$, then $I = 6.75 \text{ cd}$. The amount of luminous flux hitting the card is $\Phi = I \Omega = 0.4219 \text{ lm}$, where $\Omega = A'/z^2 = 0.0625 \text{ sr}$ is the solid angle of the card as viewed from the screen. The illuminance on the card is simply $E = \Phi/A' = LA/z^2 = 4.69 \text{ lx}$. Notice that this expression for E is what we would have obtained if we had considered luminance in the determination of the illuminance $E = L\omega = LA/z^2$, where $\omega = A/z^2$ is the solid angle of the display screen from the viewpoint of the card (see § B14). The luminance of the card (assuming Lambertian) is $L' = \rho_d E / \pi = 1.34 \text{ cd/m}^2$.

Consider the **specular reflectance** $\rho_s = 0.11$ for this configuration. With specular reflection we will use the model that the reflected luminance is proportional to the luminance of the reflected object with proportionality constant ρ_s . The black corrupting luminance L_c in the reflection is given by

$L_c = \rho_s L' = 0.148 \text{ cd/m}^2$. This seems fairly small. But suppose you have a display that is capable of contrasts of 300:1 so that the blacks—even for small areas—have luminances of $L_K = 0.333 \text{ cd/m}^2$. The corruption of L_c relative to black L_K amounts to a 44 % error. The black that you would measure is $L_m = L_K + L_c = 0.481 \text{ cd/m}^2$, and the contrast reduces to 207:1. Of course, this assumes that should you measure a small black square on a white screen, you know what you're doing. The **veiling glare** of the lens system used in the instrumentation can contribute as much as 3 % or more of the white luminance if proper care is not taken (see A2). Thus, a 3 % veiling glare error $L_g = 3 \text{ cd/m}^2$ would completely dominate any reflection errors! It would reduce the measured contrast to 33:1, which is a serious error! Veiling glare is more of a problem



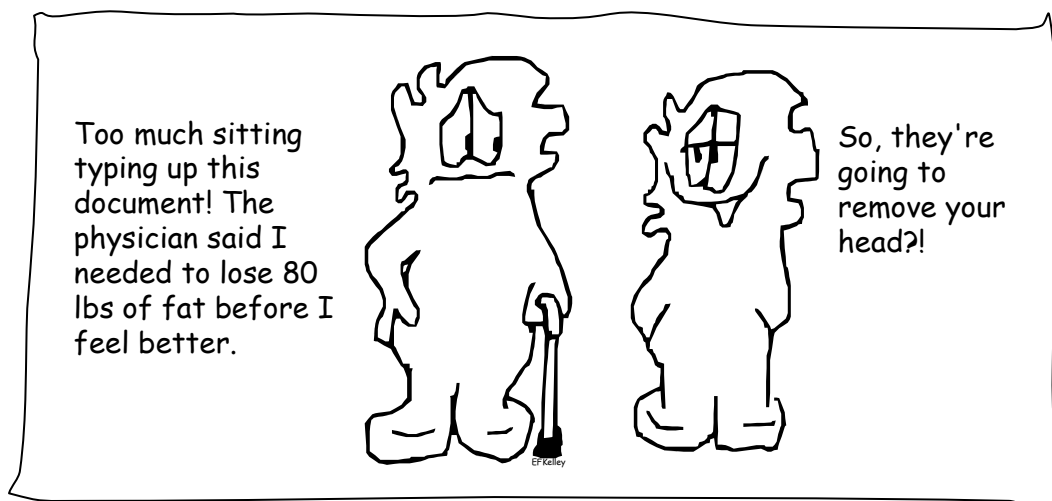


than people realize. Suppose you had a remarkably good lens with a 0.1 % glare for this arrangement. Your contribution to black would be 0.1 cd/m² which is of the same order as the black corruption from reflections. Your black measurement (including black corruption from reflection and veiling glare) would be 0.581 cd/m², and the apparent contrast would be 172:1.

Now, consider the spherical room. We want to estimate how much light will come back on our display because of general reflections in the room from the light that the display produces. The luminous intensity from the display is $I = LA \cos \theta$. Consider an element of area $dA = r^2 d\omega = r^2 \sin \theta d\theta d\phi$ on the hemisphere centered on the normal of the display with the polar axis aligned with the display normal, where $d\omega = \sin \theta d\theta d\phi$ is the solid angle of the element as viewed from the center of the display. The flux hitting dA is $d\Phi = I d\omega$. The illuminance on the element is $E = d\Phi/dA = I/r^2 = LA \cos \theta / r^2$. The luminance (assuming Lambertian) is $L' = \rho_d E / \pi = \rho_d LA \cos \theta / \pi r^2$, whereby the maximum luminance is $L'_{\max} = \rho_d LA / \pi r^2 = 0.0430$ cd/m². (If the sphere were perfectly white then $L'_{\text{white}} = LA / \pi r^2 = 0.239$ cd/m².) To obtain the illuminance reflected back on the display E' we use the idea of illuminance from the luminance of the area element: $dE' = L' d\omega \cos \theta$, and integrate over the hemisphere:

$$E' = \frac{\rho_d LA}{\pi r^2} \int_0^{2\pi} d\phi \int_0^{\pi/2} \cos^2 \theta \sin \theta d\theta = \frac{2\rho_d LA}{r^2} \frac{-u^3}{3} \bigg|_1^0 = \frac{2\rho_d LA}{3r^2},$$

where $u = \cos \theta$ is used for substitution. For our quantities, $E' = 2\rho_d LA / 3r^2 = 0.090$ lx (for a perfectly white room it would be 0.50 lx). The luminance of a perfectly white diffuse standard being hit with E' would be $L_{\text{std}} = E' / \pi = 0.0286$ cd/m² (0.159 cd/m² for a white room).





B17 REFLECTION MODELS & TERMINOLOGY

We first discuss how reflection parameters are classified, then we will discuss a specific type of reflection measurement called the bidirectional reflectance distribution function (BRDF).

B17.1 CANONICAL REFLECTION TERMINOLOGY

Abstract: Reflection terminology can be confusing. There is a standard terminology that is currently in place with which we should be familiar in order to speak carefully about reflection. The most general term is the reflectance factor R from which there arise two special cases called the reflectance ρ (either specular or diffuse reflectance) and the luminance factor β . There is also the Helmholtz reciprocity law (or theorem) that relates ρ and β for certain conditions.

REFLECTANCE FACTOR, R : The reflectance factor R is the ratio of the reflected flux from the material within a specified measurement cone to the flux that would be reflected from a perfect (reflecting) diffuser (perfectly white Lambertian surface) under the same specified illumination:

$$R = \left(\frac{\Phi_{\text{material}}}{\Phi_{\text{perfect diffuser}}} \right)_{\text{cone \& apparatus configuration}} \quad (1)$$

Note that the cone over which the measurement of light is made must be clearly specified. All the geometry of the apparatus used, detector, source, structure, etc., must be carefully specified in order to make accurate and reproducible measurements of reflective materials. Such a specification is required by the use of the reflectance factor.

There are two special cases of interest: (1) When we shrink the measurement cone to zero we have the luminance factor β :

$$\Omega \rightarrow 0, \quad R \rightarrow \beta \quad (\text{luminance factor}). \quad (2)$$

The luminance factor essentially assumes that the size of the detector cone doesn't matter, i.e., the size of the lens of the detector doesn't affect the results (it can!).

(2) When we extend the cone to a hemisphere we have the diffuse reflectance ρ :

$$\Omega \rightarrow 2\pi, \quad R \rightarrow \rho \quad (\text{diffuse reflectance}). \quad (3)$$

So, we have to be careful about using the term “reflectance” without realizing that it is a very specific type of reflection property.

NOTATION: In what follows, because the source and detector can be rather well defined, the reflection parameters R , ρ , or β can have a subscript denoting the geometrical configuration used to make the measurement. This is a **source/detector notation** where a number specifies the angle of the source or detector from the normal and “d” specifies that the hemisphere is used as the source or detector. For example, $\rho_{d/45}$ is the diffuse reflectance measured using a diffuse source with the detector at 45° , $\rho_{45/d}$ is the reflectance with the source at 45° and the reflected light is measured using a diffuse detector like an integrating sphere.

REFLECTANCE, ρ : The ratio of the entire reflected flux Φ_r to the incident flux Φ_i for a given apparatus configuration:

$$\rho = \frac{\Phi_r}{\Phi_i} \bigg|_{\text{apparatus configuration}} \quad (4)$$

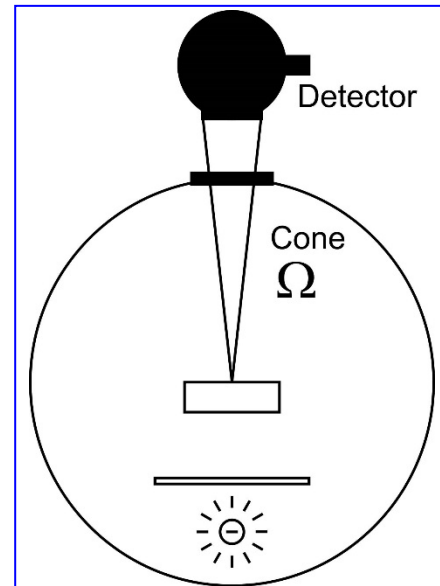


Fig. 1. Example of a specified measurement cone in a reflectance factor measurement using diffuse illumination.

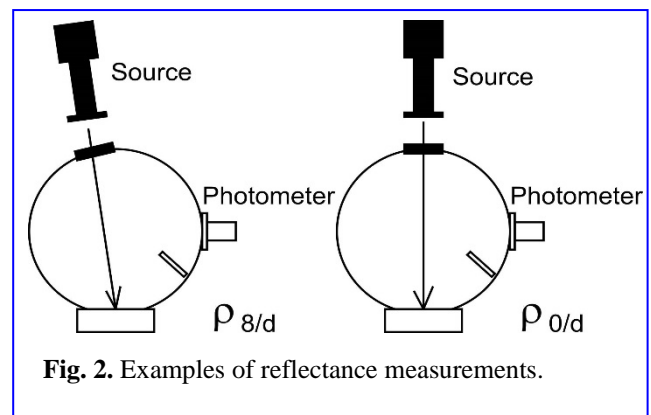


Fig. 2. Examples of reflectance measurements.



There are two types of reflectance:

Diffuse Reflectance ρ_d (we will often use ρ without the subscript): The above ratio where all the diffusely reflected flux is collected over the hemisphere $\Omega = 2\pi$. “Diffuse” means scattered out of the specular direction.

Specular (or Regular) Reflectance ρ_r (we will often use ζ instead to avoid complicated subscripts): The above ratio where the specularly reflected flux is collected in the specular direction without diffusion contributions. The specular direction is like the reflection off of a flat mirror as dictated by the laws of geometrical optics.

LUMINANCE FACTOR, β , AND LUMINANCE COEFFICIENT, q : The luminance factor β is the ratio of the luminance of the object to that of the luminance of a perfect reflecting diffuser (perfectly white Lambertian material) for a given apparatus configuration:

$$\beta = \frac{\pi L}{E} \bigg|_{\text{apparatus configuration}} \quad (5)$$

The luminance coefficient is proportional to the luminance factor:

$$q = \frac{\beta}{\pi} \quad (\text{luminance coefficient}) \quad (6)$$

This gives us four reflection terms to keep straight.

NOTE ON UNITS: Some are still using other system of units than the SI units (see table below). There can arise quite a bit of confusion because of this problem. The above was all derived based upon SI units. However, using Imperial units, the reflection equations can be a little different because the π factor in Eq. (5) is absorbed in the unit of measure. See the tables in § B1 for the proper conversions between cd/m^2 and fL or lx and fc .

HELMHOLTZ RECIPROCITY LAW: Claims that the luminance factor for a source/detector configuration d/θ is equal to the diffuse reflectance for a source/detector configuration of θ/d :

$$\beta_{d/\theta} = \rho_{\theta/d} \quad (7)$$

Suppose we purchase a reflectance standard that claims a reflectance of $\rho_{\text{std}} = 0.99$. Such a value was probably obtained using the apparatus to the right in Fig. 4 with $\theta = 0$, that is $\rho_{\text{std}} = \rho_{0/d} = 0.99$. We can place the standard in an illuminated integrating sphere as in the left side of Fig. 4 and use a luminance factor of $\beta_{d/0} = 0.99$. *Don't use such a calibration in any other configuration unless you are certain such a calibration holds for that configuration.* The basic lesson is: Geometry is often very important.

REFERENCES:

- [1] *Absolute Methods for Reflection Measurement*, CIE Publication No. 44, 1990.
- [2] *A Review of Publications on Properties and reflection Values of Material Reflection Standards*, CIE Publication No. 46, 1979.

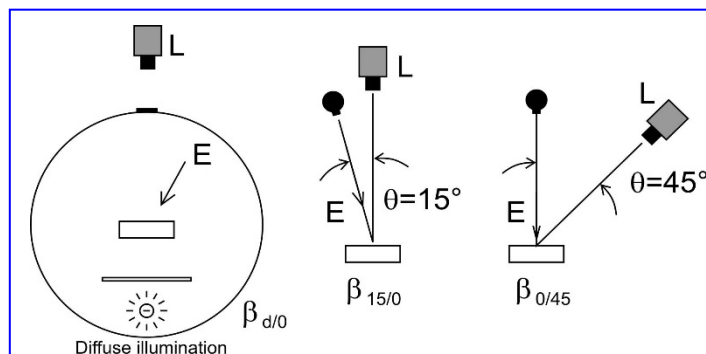


Fig. 3. Examples of luminance-factor measurements and the source/detector notation.

	SI Système International d'Unités (International System of Units)	Imperial
Luminance, L	in cd/m^2	in fL
Illuminance, E	in lx	in fc
Luminance Factor, β	$\beta = \frac{\pi L}{E}$	$\beta = \frac{L}{E}$
Comment	Used in this document. ☺	Not used here. ☹
See tables in B1 for conversions between SI and Imperial units.		

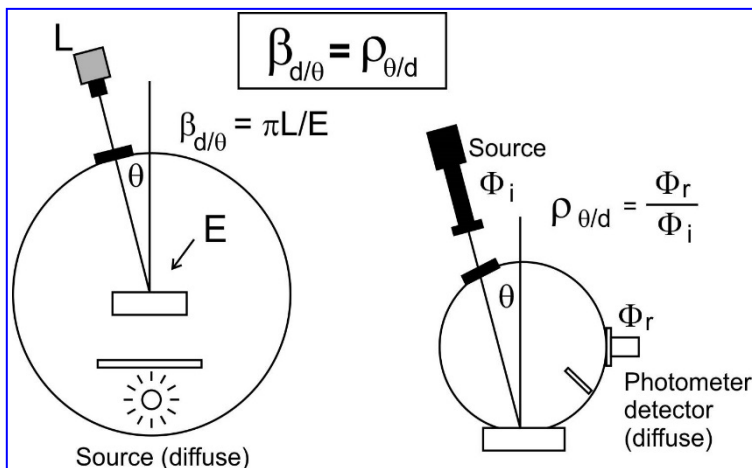


Fig. 4. Illustration of the Helmholtz reciprocity law.



B17.2 BRDF FORMALISM AND THE COMPONENTS OF REFLECTION

Abstract: A model of the bidirectional reflectance distribution function (BRDF) is provided, and three types of reflection are discussed: specular (regular, mirror-like producing a distinct image), and two types of diffuse reflection, Lambertian and haze. A fourth type of reflection called matrix scatter is also discussed.

NOTE: Reflection characterization is still under study. Overly simplistic models do not adequately characterize reflection for modern displays. This material is presented as an annex. No measurement is currently specified in this measurement standard to measure the BRDF or its parametric representation. When the measurement is simplified sufficiently to provide an adequate parameterization of reflection, then a procedure will be added. Until then, this represents an introduction to a more rigorous model of reflection. This method has application to three of the four types of reflection: Lambertian, haze, and specular. However, it does not work well for matrix scatter if the display front surface is specular; the results become very sensitive to apparatus configurations making reproducibility extremely difficult. However, if the front surface is diffusing, then matrix scatter appears as a complicated haze and can be measured with BRDF techniques.

BRDF FORMALISM:

This reflection model is based on the bidirectional reflectance distribution function (BRDF). [1] Neglecting any wavelength and polarization dependence, the BRDF is a function of two directions, the direction of the incident light (θ_i, ϕ_i) and the direction from which the reflection is observed (θ_r, ϕ_r) in spherical coordinates as shown in Fig. 1. The BRDF relates how any element of incident illuminance dE_i from direction (θ_i, ϕ_i) contributes to a reflected luminance dL_r observed from direction (θ_r, ϕ_r) :

$$dL_r(\theta_r, \phi_r) = B(\theta_i, \phi_i, \theta_r, \phi_r) dE_i(\theta_i, \phi_i), \quad (1)$$

where $B(\theta_i, \phi_i, \theta_r, \phi_r)$ is the BRDF. (In the literature the BRDF is often denoted by f_r . We use B to avoid complicated subscripts and confusion with other uses of “ f ” within the display industry.) By integrating over all incident directions in space, the luminance $L_r(\theta_r, \phi_r)$ observed from any direction (θ_r, ϕ_r) can be determined by

$$L_r(\theta_r, \phi_r) = \int_0^{2\pi} \int_0^{\pi/2} B(\theta_i, \phi_i, \theta_r, \phi_r) dE_i(\theta_i, \phi_i). \quad (2)$$

The illuminance contributions dE_i arise from luminance sources in the room. For each element of solid angle $dA_i/r_i^2 = d\Omega = \sin\theta_i d\theta_i d\phi_i$ at a distance r_i from the screen there is a source luminance $L_i(\theta_i, \phi_i)$ producing illuminance

$$dE_i = L_i(\theta_i, \phi_i) \cos\theta_i d\Omega = L_i(\theta_i, \phi_i) \cos\theta_i \sin\theta_i d\theta_i d\phi_i, \quad (3)$$

where the cosine term accounts for the spreading of the illuminance over a larger area as the inclination angle increases.

The diffuse reflection model for a Lambertian surface relates the reflected luminance to the total illuminance by

$$L = qE, \text{ where } q = \rho/\pi \quad (\text{Lambertian}) \quad (4A)$$

is the luminance coefficient, and ρ is the diffuse reflectance. Specular reflection is characterized in terms of the luminance of the source L_s and the specular reflectance ζ so that the reflected luminance is given by

$$L = \zeta L_s. \quad (\text{specular}) \quad (4B)$$

This is the specular reflection that produces a distinct image as does a mirror; see “distinctness-of-image gloss,” “specular reflection,” “specular,” in [2]; and “regular” in [4]. In these cases, the term “specular” or “regular specular” refers to reflection without diffusion away from the specular direction. In this document specular reflection will be used to refer to the component of reflection that produces a distinct mirror-like image without diffusion as in Eq. (4B). Since the term “diffuse” when use with reflection refers to light energy that is scattered out of the specular direction, we will define “diffuse-

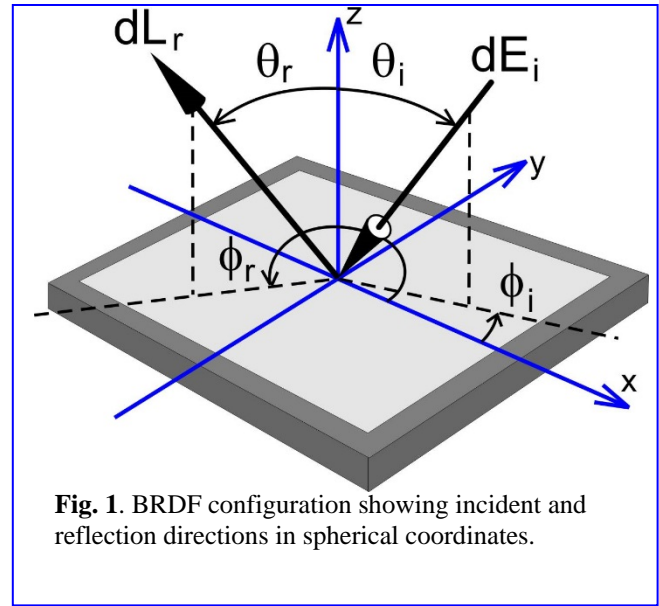


Fig. 1. BRDF configuration showing incident and reflection directions in spherical coordinates.



Lambertian" to mean the Lambertian-like reflection expressed in Eq. (4A), and we will generally refer to this as the Lambertian reflection. Lambertian and specular reflection models are inadequate to characterize reflection from all displays. There is a third type of reflection that we will call "diffuse-haze" or simply "haze," for want of a better term (see ASTM E-284 [2] and D-4449 [3]).¹

Many screens today have surfaces that scatter some of the specular light energy into other directions—a process called diffusion; the object causing the diffusion is called a diffuser (see [2]). Refer to Fig. 2: Using a point light source 200 mm to 500 mm away from the screen (such as a bare flashlight bulb), if you can see a distinct image of the source in the reflection then the surface has a non-trivial (regular, mirror-like) specular component that produces a distinct virtual image. If you can see a general dark-gray background that is relatively uniform across the screen, then the screen has a non-trivial diffuse-Lambertian component. If you see a fuzzy patch of light surrounding the image of the bulb (or in the specular direction) then the screen also has a diffuse-haze component—we will generally refer to the diffuse-haze component as the

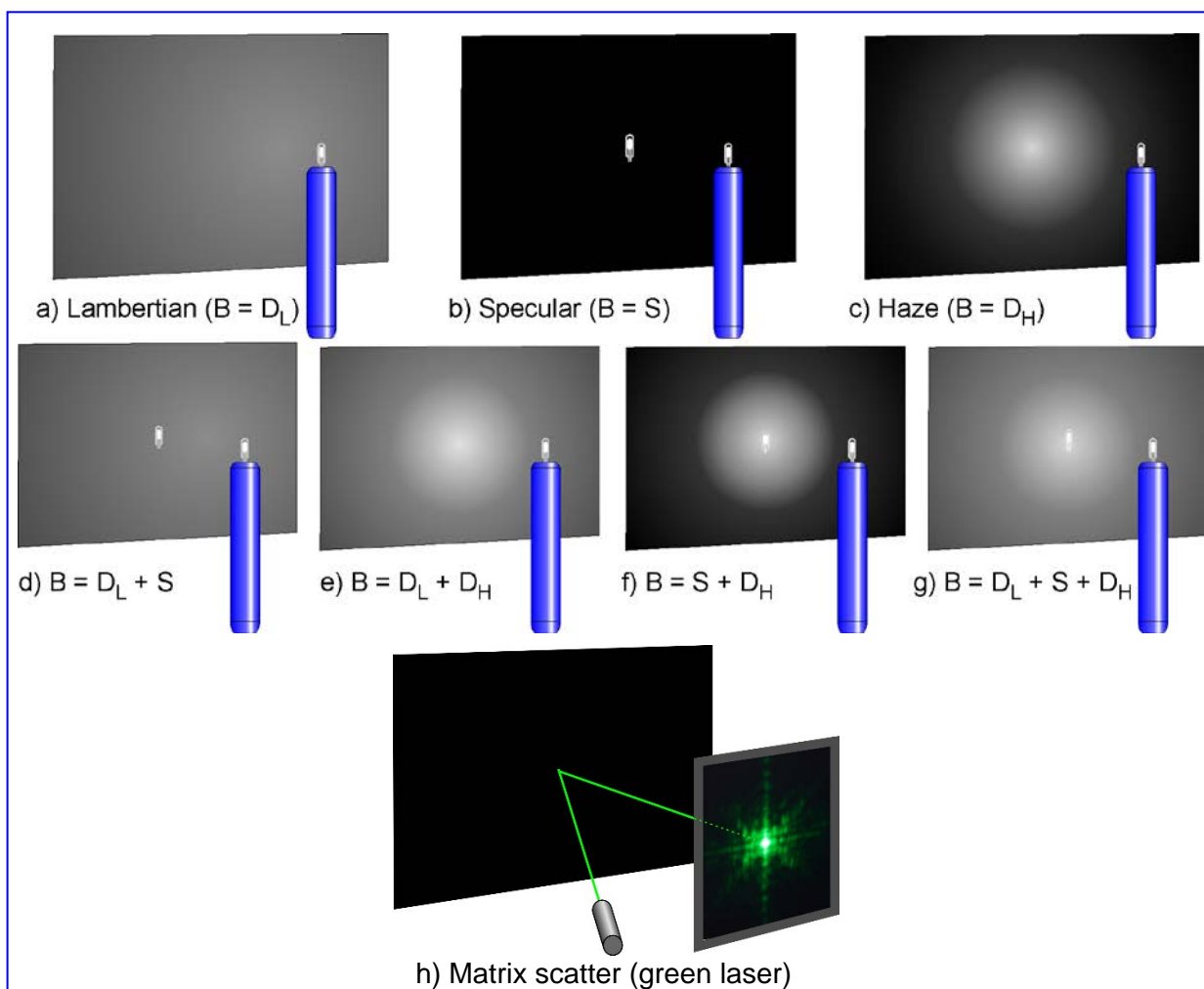


Fig. 2. Illustration of four types of reflection found in modern electronic displays. B refers to the BRDF that can have a diffuse-Lambertian (or just Lambertian) component, D_L , a mirror-like specular component that produces a distinct image, S , and a diffuse-haze (or just haze) component, D_H . A fourth type of reflection (h) shown here is matrix scatter that has a very strong specular component. One of the four components must exist. There are four combinations of the three components, Lambertian, haze and specular, illustrated in (d)-(g). If matrix scatter occurs behind a diffusing front surface then it will manifest itself as a complicated haze that can be measured by BRDF techniques. Any or all of the components can exist nontrivially, or one component can dominate while the other components make a trivial contribution to the reflection as in the case in the first three illustrations and last (a)-(c), (h).

haze component for shorthand. In fact, attempts are being made to obtain the BRDF from a measurement of the reflection

¹ Michael Becker is credited with starting the use of the term "haze" to provide a name for the fuzzy reflection. His use of the term "haze" was based upon the usage found in the ASTM documents cited.



distribution from a point source, but the measurement is very difficult and can be compromised because of glare arising in the lens system used. If you see a star pattern emanating from the specular distinct image then you have matrix scatter; often there will be different colors visible because of the diffraction pattern generating the matrix scatter. In Fig. 2 we illustrate matrix scatter using a green laser whereby the matrix scatter is visible on a rear-projection screen or frosted glass (a white card will also work well). For the case shown in Fig. 2h the display has a front surface that is glossy generating a specular distinct image that is much brighter than the surrounding matrix scatter.

It is important to realize that not all components of reflection need to be observable, but least one component will exist for any display that has a surface or covering (Fig. 2a, b, c, h). There are displays that have entirely quasi-Lambertian diffuse surfaces (e.g., white xerographic copy paper—Fig. 2a). There are displays that don't have a specular component and have only a haze component with the Lambertian component being negligible (10^{-4} the size of the haze reflection peak in the specular direction or less—Fig. 2c, many desktop computer displays exhibit only a nontrivial haze component). When the reflection of a point light source is observed in screens with only a haze component, only a fuzzy patch of light is seen in the specular direction and no distinct image of the source is observed. There are displays that don't have a substantial haze component and only exhibit specular and quasi-Lambertian reflections—Fig. 2d—and some of these often exhibit a matrix scatter in addition to the specular component. In all these cases, a thin-film antireflection coating can be added to further reduce the reflections from the front surface of the screen making the surface of the display appear quite dark. This is especially true in the case of Fig. 2b, 2c, or 2f where the Lambertian component is either absent or negligible. Another way to view the BRDF is to hit the screen with a narrow laser beam and view the reflected light against a large white card in a dark room as in Fig. 2h. The distribution of the light on the white card is the projection of the BRDF onto a plane.

We can capture the three types of reflection (specular, Lambertian, and haze) explicitly with the BRDF formalism in terms of three additive components: The diffuse part of the reflection results from a combination of two components: the Lambertian D_L (or diffuse-Lambertian) component and the haze D_H (or diffuse-haze) component

$$D = D_L + D_H. \quad (5)$$

The diffuse components will combine with the specular component S to give us a BRDF that is composed of three components:

$$B = S + D_L + D_H, \quad (6)$$

where the components are defined by [1]

$$\begin{aligned} S &= 2\zeta \delta(\sin^2 \theta_r - \sin^2 \theta_i) \delta(\phi_r - \phi_i \pm \pi), \\ D_L &= q = \rho / \pi, \\ D_H &= H(\theta_i, \phi_i, \theta_r, \phi_r). \end{aligned} \quad (7)$$

Here, ζ is the specular reflectance and ρ is the hemispherical diffuse reflectance. In the specular term the delta functions $\delta(\dots)$ are generalized functions that, roughly speaking, select the value of a function within an integral:

$$f(a) = \int_{-\infty}^{+\infty} f(x) \delta(x - a) dx. \quad (8)$$

These functions simply assure that the specular contribution only comes from whatever source may be located in the specular direction (the same angle from the normal on the opposite side of the normal). They provide for a mirror-like distinct virtual image of the source in the viewed reflection. When we integrate this three-component BRDF over all incident illumination directions by combining Eqs. 4-7, the reflected luminance is given by

$$L_r(\theta_r, \phi_r) = qE + \zeta L_s(\theta_r, \phi_r \pm \pi) + \int_0^{2\pi} \int_0^{\pi/2} H(\theta_i, \phi_i, \theta_r, \phi_r) L_i(\theta_i, \phi_i) \cos(\theta_i) d\Omega. \quad (9)$$

The first term is the familiar Lambertian reflection where E is the total illuminance from all directions, and the luminance coefficient q is expressed in terms of the Lambertian reflectance ρ by $q = \rho / \pi$. The second term is the familiar specular reflection whereby the specular contribution is regulated by the specular reflectance ζ . The specification of $(\theta_r, \phi_r \pm \pi)$ simply selects the light from the viewing direction (θ_r, ϕ_r) reflected about the normal (z-axis), i.e., the specular direction associated with the viewing direction. The last term is the haze contribution.

Because the full BRDF is a four-dimensional function (actually six-dimensional, but we are neglecting polarization and wavelength here), to measure it completely would require a large amount of data and the measuring instrumentation would be expensive. However, because we are using displays, we are often able to take advantage of some simplifications that reduce the amount of data required so that this formalism is manageable. First, note that most displays are viewed from the normal direction (or at least from one direction), and the range of angles to observe the entire screen from the normal position are usually on the order of $\pm 30^\circ$ or less. For electronic displays, it is often found that the shape of the BRDF does not



change appreciably over this range—see Fig. 3. Thus, a reduced BRDF $B(\theta_i, \phi_i) \equiv B(\theta_i, \phi_i, 0, 0)$ is often adequate for many reflection characterizations of displays. In the following the subscript “i” denoting the incident illumination will be dropped from the spherical coordinates and is to be understood. We will from now on be considering the reduced BRDF as being adequate for display use:

$$B(\theta, \phi) \equiv B(\theta, \phi, 0, 0).$$

If the BRDF is seen to be symmetrical about the specular direction then the BRDF is independent of ϕ , $B(\theta, \phi) = B(\theta)$. When the reflection of a point source is observed for a screen having a rotationally symmetrical BRDF the haze reflection will appear to be perfectly round without any spikes. For such a case, acquiring a suitable BRDF for displays amounts to taking an in-plane BRDF where the detector is held near the normal of the screen and the source is rotated about the normal in the horizontal plane. However, because of structure behind the front surface of the display, this last reduction is sometimes not possible, i.e., the BRDF is not always rotationally symmetric about the normal—see Fig. 4. For such screens, the BRDF is no longer a simple function to measure. This is often the case when there is matrix scatter behind a diffusing front surface producing a haze that is not rotationally symmetric about the normal but exhibits various spikes.

Methods to obtain the BRDF are documented and will not be reviewed here. [5-8] When there is a non-trivial specular and non-trivial haze component, the measurement of the BRDF must be made carefully using well-designed apparatus where the signature of the apparatus can be used to better understand the results. [7,8] (The signature is obtained by measuring the BRDF of a specular sample such as a good mirror or black glass.) When there is just a haze component—as with a number of FPDs—the BRDF measurement can be made more easily than when a non-trivial specular component exists in addition to the haze. In Fig. 5 we show the BRDF of a display-simulation sample that possesses all three components of reflection such as illustrated in Fig. 2g. The specular component is manifested by a sharp peak, the haze profile has both a peak value and a width, and the Lambertian component manifests itself as the quasi-constant background; the Lambertian component appears constant on a log scale but will show a slope on a linear scale. In order to resolve the delta-function-like behavior of the specular component against the haze peak, the apparatus needs to have a resolution of 0.2° or less. Decreasing the resolution of the apparatus

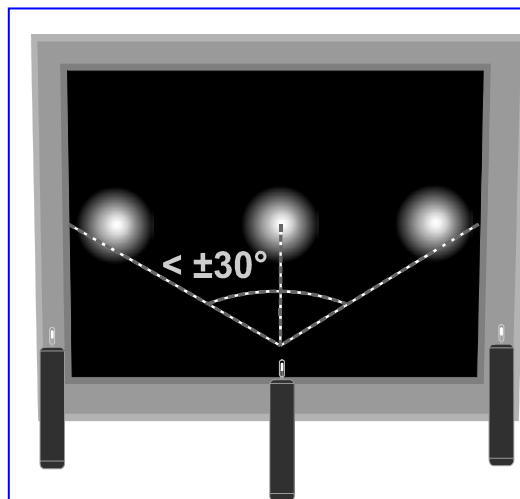


Fig. 3. For many displays, the BRDF appears to have approximately the same shape as viewed all over the screen from a single observation point near the normal.

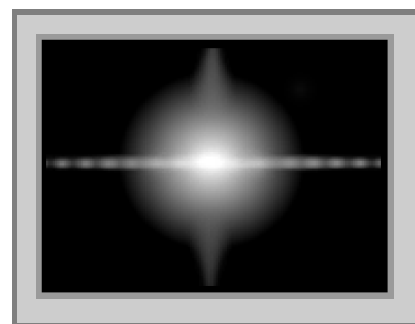


Fig. 4. A display BRDF that is not rotationally symmetric.

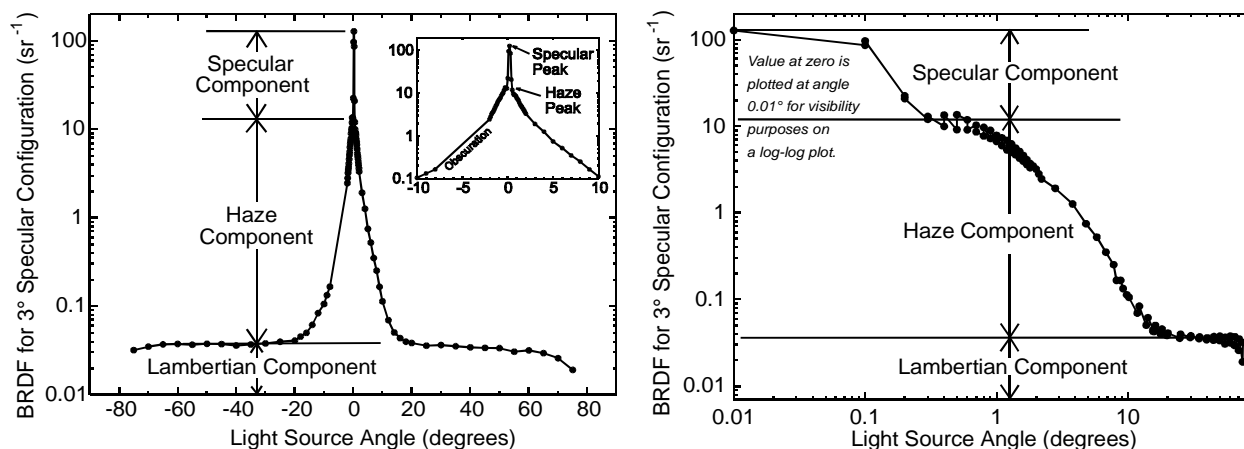


Fig. 5. BRDF of sample material with obvious Lambertian component. Inset shows detail of peak. The resolution of the BRDF apparatus is 0.2° , and a point source is employed to obtain the BRDF. Two presentations of the same data are provided; the log-log plot is useful for revealing the details at the peak.



(increasing its acceptance area or angular aperture) will diminish the distinctness of the specular peak until it becomes irresolvable as a separate peak and is smeared in with the haze profile. The resolution of the apparatus depends upon both the detector and source configuration. You will note that, very roughly speaking, the specular component is roughly ten times the haze peak that is roughly 100 times the Lambertian component. This kind of range of magnitudes in the reflection components can be found in a number of displays that exhibit all three components. The fall-off at the angles above 60° may be due to the increase in the reflection of a surface at grazing angles where even a matte surface can appear specular. The Lambertian component would be the flat area indicated.

To better see how these three components are related, consider a very small uniform disk of light used as a source having a solid angle Ω from the center of the screen and luminance L_s . Let's suppose we are looking in the specular direction at the reflection of the small disk, and we determine the luminance L of the center of the reflected image—see Fig. 6. Let the haze profile H have a peak of magnitude h in the specular direction. Since the size is small, the integration in Eq. 9 is simply $hL_s\Omega = hE_s$, where $E_s = L_s\Omega$ is the illuminance from the source onto the screen. Then Eq. 9 simplifies to

$$L = (q + h)E_s + \zeta L_s. \quad (10)$$

Thus, we see that haze is like Lambertian reflection in that it is dependent upon the magnitude of the illuminance, but it is like specular reflection in that it is peaked in the specular direction. As we move the source closer to the screen (or further away) the term proportional to the illuminance increases (or decreases), but the specular term remains the same, independent of distance. This is why the eye sees the three components as separate for they each act in different ways with respect to a source of light. In fact, specular and Lambertian reflection components are the two extremes of the haze profile. One extreme shape of the haze profile (or BRDF) is to be flat (constant) as a function of angle for the Lambertian reflection. The other extreme shape of the haze profile is a delta function for the idealized specular reflection. (Of course, the delta function is a mathematical abstraction of a practical situation, but it is a convenient mathematical construct to permit the parametric characterization of the BRDF and, hopefully, better enable calculations of reflection from luminance distributions given the screen reflection properties.)

This idea can be extended further to permit the separation of the specular peak from the haze peak, where we are assuming that both components are present and nontrivial. (This may someday become a measurement method in this document called the variable radius source method for separating and extracting the specular component and haze peak.) The source can have several apertures ranging from 1° subtense and smaller. As the radius of the aperture approaches zero, the illuminance approaches zero, but the luminance of the specular component stays proportional to the luminance of the source. Of course, the LMD would be required to be able to measure small sources and have a measurement field angle less than a minute of arc. Expressing the illuminance explicitly in terms of the source parameters we have,

$$L = \zeta L_s + \left[(q + h) \frac{\pi L_s \cos \theta_s}{d^2} \right] r^2, \quad (11)$$

where d is the distance to the source and r is its radius, and where we show the r -dependence explicitly. Typically, for such displays the Lambertian component q is 0.05 or less and the haze peak h is 10 sr^{-1} , we can ignore the Lambertian component. We are left with the form

$$L = c + ar^2, \quad (12)$$

where $\zeta = c/L_s$ and $h = a d^2 / (\pi L_s \cos \theta_s)$. Thus, if we fit the data to a symmetric sixth order polynomial

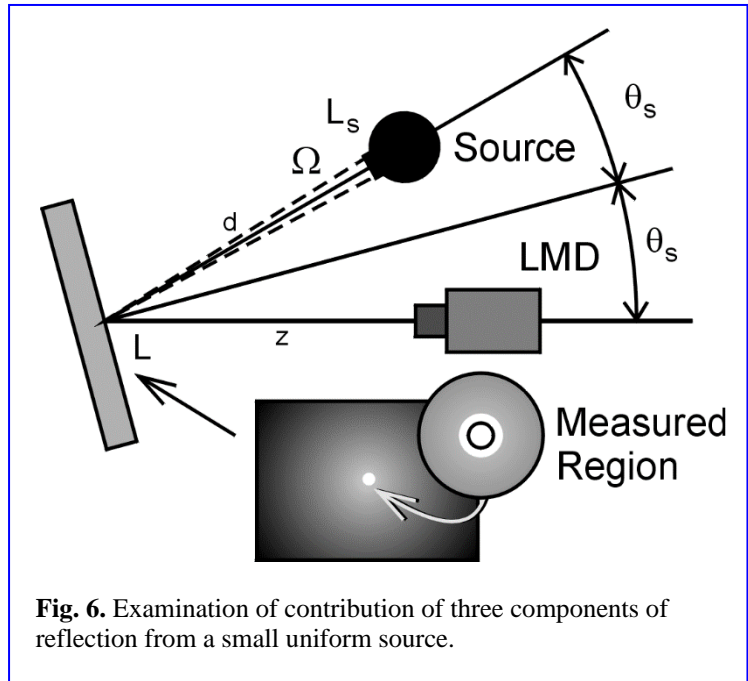


Fig. 6. Examination of contribution of three components of reflection from a small uniform source.

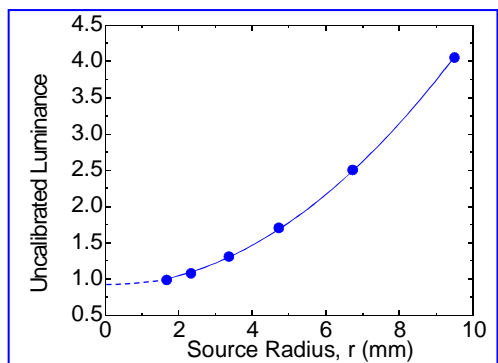


Fig. 7. Luminance as a function of radius exhibiting a haze peak and specular component.



$$L(r) = c + ar^2 + fr^4 + gr^6, \quad (13)$$

we can then obtain values for c and a and thereby extract the specular component and haze peak. The reason for using a sixth order polynomial instead of a second order is that Eq. (11) is only true for very small radii, and a sixth order polynomial is needed to fit the data as exhibited in Fig. 7.

When the front surface of the display can be placed in close proximity to the pixel surface, e.g., 1 mm or so, the specular component can be completely eliminated in favor of a haze component with a trivial Lambertian component in the background. When the front surface of the display cannot be placed near the pixel surface, then a strongly diffusing front surface cannot be used because it would obscure the pixel detail. This can be demonstrated by trying to read printing through wax paper or frosted glass held approximately 10 mm above the printing compared to the wax paper or frosted glass placed directly on the printing.

Many measurement methods used to attempt a characterization of reflection mix the components in different ways. Whenever haze or matrix scatter is dominant they hinder the reproducibility of the measurement. In such cases the measurement result can be *very* sensitive to the apparatus configuration and its detailed geometry.

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B17.3 Bidirectional Scatter Distribution Function From the Point-Spread Function (PSF2BSDF)

ABSTRACT

A special subset of the bidirectional reflectance distribution function (BRDF), the in-plane BRDF, is commonly measured with a goniometer where the LMD inclination can be systematically varied within the plane of light incidence (see, *e.g.*, Fig. 1 of section 11.13 of IDMS (Diagnostic Validation of the BRDF system) or, alternatively, Fig. 1 of section B.17.2 of IDMS (BRDF formalism and the components of reflection).

When the scatter distribution is locally not symmetric about the specular direction, a 2D scan with high resolution would be needed to measure the scatter profile. This could be quite time consuming even for a motorized goniometric system. This section outlines an imaging method that can be used to determine the bidirectional scatter distribution function (BSDF) from a measurement of the point spread function (PSF). The term BSDF comprises the BRDF and the bidirectional transmittance distribution function (BTDF) as well.

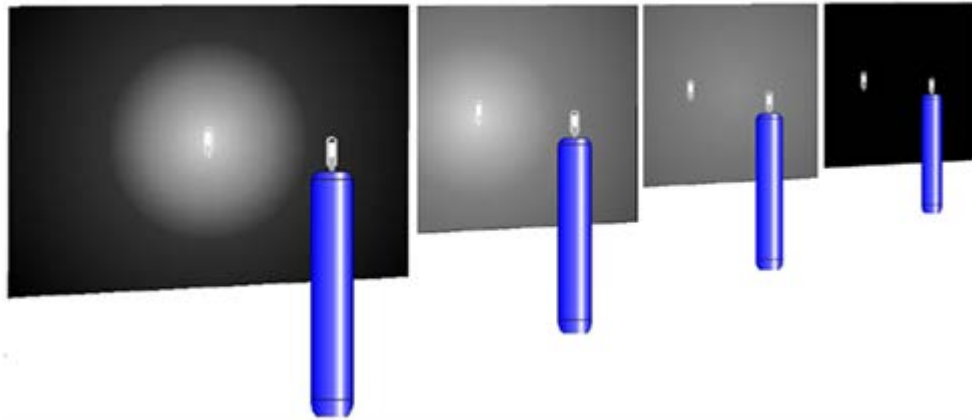


FIGURE B17.12. Illustration of the lateral distribution of light from a point source (PSF) reflected from 4 different planar samples that are all featuring a mirror component (from left to right: haze + mirror, haze + Lambertian + mirror, Lambertian + mirror, mirror only).

When uniform planar samples are illuminated by a small light source (*point light source*, PLS), each area element on the sample surface receives light from one specific direction and the eye of the observer receives light from that area element along a second specific direction. The lateral distribution of reflected light that is seen by the observer or recorded by an imaging LMD is called the *point spread function*, PSF. The main components of reflection, *i.e.*, the mirror component, the Lambertian, *i.e.*, uniform diffuse, and the haze component are distinctly obvious in the PSF.

This section introduces a method to determine the BSDF from the PSF in the vicinity of the specular direction [B17.11]-[B17.13] and the individual reflection components [B17.14]-[B17.16] from the PSF. Even though this section focuses on scattering and diffraction during reflection, the method can also be applied to scattering and diffraction during transmission.

Introduction of the angle θ^* between the specular beam at a specific location and the received beam from the same location is based on the shift invariance of scattering in direction cosine space with respect to the angle of light incidence as described by Harvey [B17.17]. Since the scattering distribution remains basically constant for small angles of light incidence ($< 20^\circ$), this method references the scattering to the local specular direction. The new azimuth angle, ϕ^* , is just the projection of the azimuth of the location (x, y) on the plane of the LMD detector array to assure correct analysis of diffraction from gratings. This method is the basis for high-resolution BSDF measurement in the vicinity of



the specular direction with imaging LMDs. Measurement of in-plane variations of reflection and transmission far from the specular direction are possible when the LMD is used as a spot meter.

The 1D variant of this method with a linear light source has been in industrial use for evaluation of reflection and transmission distribution functions of scattering layers [B17.18].

B17.3.1 Measurement Setup

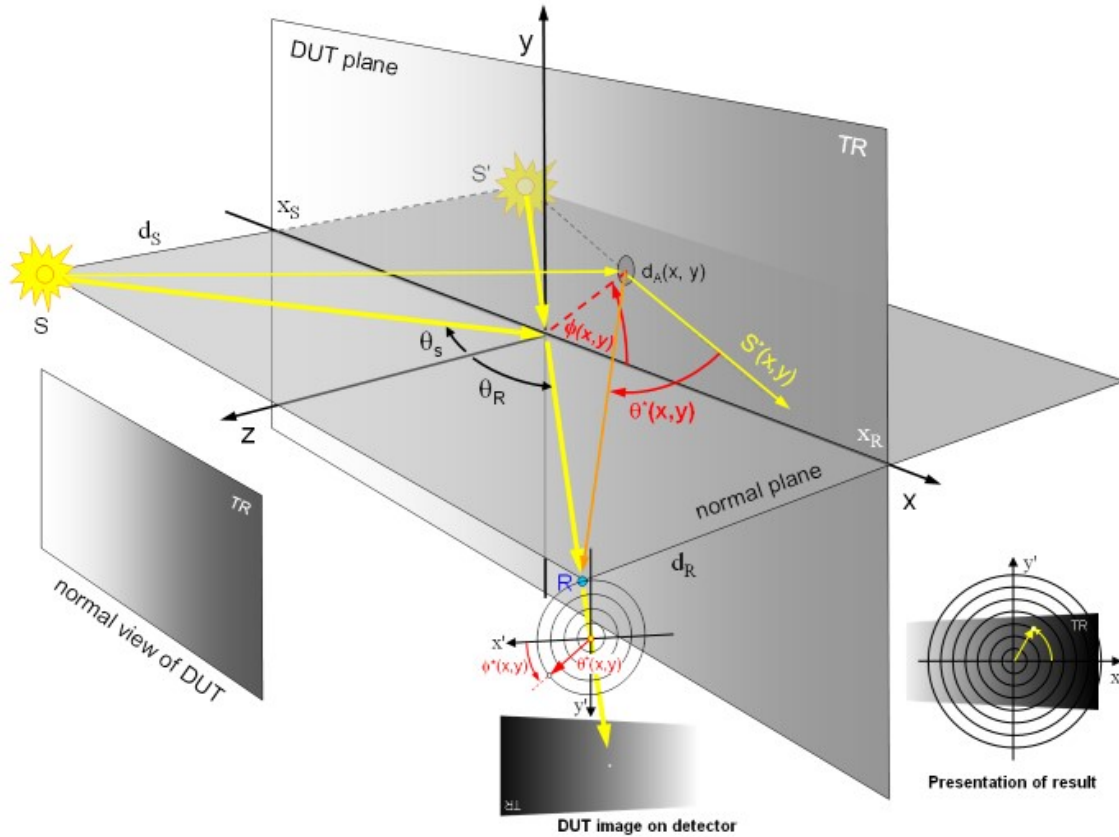


FIGURE B17.13. Geometry of the measurement setup with the normal view of the DUT, the DUT image on the detector array (rotated by 180°) and the angles θ^* and ϕ^* of the polar coordinate system on the detector array centered about the specular beam. The isotropic point light source, S , is shown for both the reflective and transmissive case (S'), R is the pinhole aperture of the LMD (receiver). θ_R and θ_S are usually smaller than 20° but are exaggerated in the figure for clarity.

The measurement setup is arranged such that the specular beam from center of the DUT ($x = 0$, $y = 0$) is located in the center of the LMD detector array ($x' = 0$, $y' = 0$). That means that the angle of inclination of light source and LMD optical axis are identical, $\theta_R = \theta_S$. R is the entrance pupil of the LMD, which is modeled as a pinhole camera.

- Each intensity value at the location (x, y) on the DUT, $I(x, y)$, is assigned two spherical coordinates, $\theta^*(x, y)$ and $\phi^*(x, y)$. Both angles θ^* and ϕ^* are functions of the x, y -coordinates of the location (x, y) . The former is the angular difference of the received beam and the local specular direction and the latter is the projection of the azimuth ϕ on the plane of the detector array.
- Each location (x, y) on the DUT corresponds to a location (x', y') on the detector array. The image of the DUT on the detector array is rotated about the LMD optical axis about 180° .
- Starting with the lateral intensity distribution (tristimulus values in the general case) on the detector array, $I(x', y')$, for each detector element (LMD pixel), x and y are calculated and from those the respective pairs of angles, θ^* , $\phi^* = f(x, y)$.

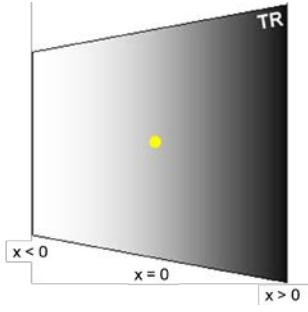


FIGURE B17.14. View of the DUT along the direction of the LMD optical axis. The DUT reflected luminance is higher on the side closer to the light source ($x < 0$), the closer edge ($x > 0$) appears larger and darker. The top-right corner is marked (TR) for identification of DUT orientation.

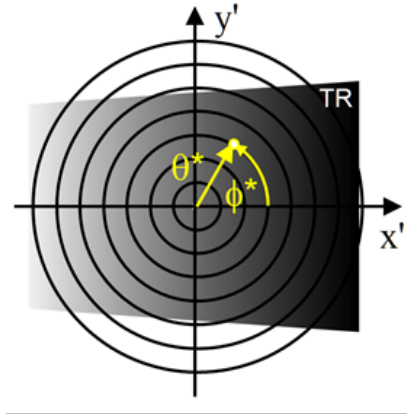


FIGURE B17.15. Image of the DUT as seen along the LMD axis with the θ^* , ϕ^* polar coordinate system centered about the specular ray.

B17.3.2 From the DUT to the LMD Detector Array – Pinhole Camera Model

With the following conventions,

Coordinate system on LMD detector array	x' , y' , and z'
Spherical coordinates	θ^* and ϕ^* in the $x'y'$ -system
Coordinate system on DUT	x , y , z , θ , and ϕ ,

and with the geometry of the measurement setup specified by the quantities according to FIGURE B17.13:

- Point light source, S, by distance, d_S , from the DUT plane and angle of inclination, θ_S .
- Receiver pupil, R, by distance, d_R , from the DUT plane and angle of inclination, θ_R ,

and with the origin of the coordinate system, x', y' , given by the location of the specular ray on the detector array (x'_{sp}, y'_{sp}), for all locations on the detector array, (x', y'), we calculate the corresponding locations (x, y) on the DUT as:

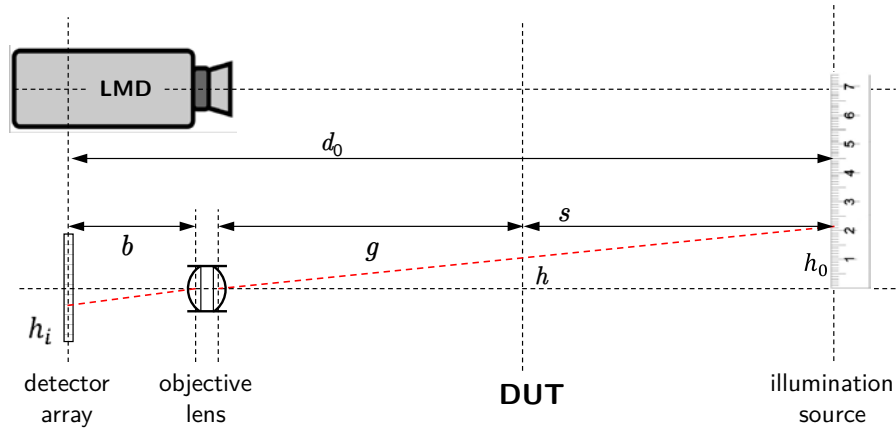
$$x = x' \cdot \frac{g}{b \cos \theta_R - x' \sin \theta_R} \quad (\text{B17.21})$$

$$y = y' \cdot \frac{g \cos \theta_R}{b \cos \theta_R - x' \sin \theta_R} \quad (\text{B17.22})$$

where b is the image distance and g is the object distance according to FIGURE B17.16. Since in most cases the position of the entrance pupil and the principal planes are not known, we rely on the distances that can be measured with reasonable accuracy: (1) the distance from the object to the detector array, d_0 , the height of object and image, h_o , d_i , respectively, and the distance between the light source and the DUT, s . These measured values can then be used to determine b and g :

$$\frac{h_i}{b} = \frac{h_o}{g + s}; \quad g = \frac{h_o d_0 - h_o s - h_i s}{(h_i + h_o)}, \text{ and } b = \frac{h_i}{h_o} (g + s) \quad (\text{B17.23})$$

with
$$m = \frac{h_i}{h_o}; \quad g = \frac{d_0 - s(m + 1)}{(m_i + 1)}, \text{ and } b = m(g + s) \quad (\text{B17.24})$$


 FIGURE B17.16. Arrangement for the determination of b and g .

B17.3.3 Deduction of Equations (B17.21) and (B17.22)

Equations (B17.21) and (B17.22) above are derived based on the geometry illustrated in FIGURE B17.17, where b is the image distance and g is the object distance.

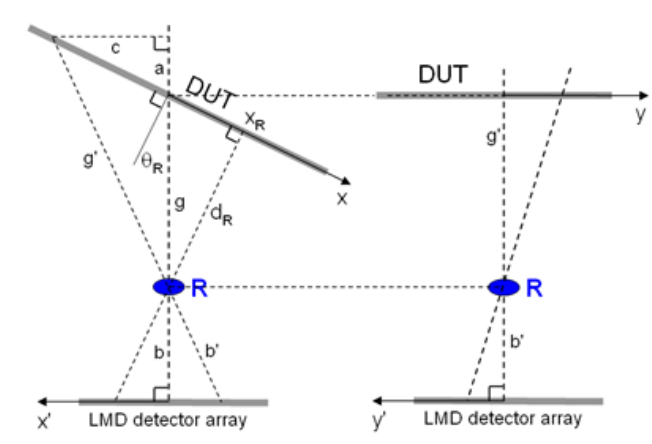


FIGURE B17.17. Geometry of pinhole camera, DUT, and detector array, *i.e.*, image plane. The left and right side is the top and side view, respectively.

Using the following geometric relations,

$$\sin \theta_R = \frac{x_R}{g} \text{ and } \cos \theta_R = \frac{d_R}{g} \quad (\text{B17.25})$$

$$a = x \cdot \sin \theta_R \text{ and } c = x \cdot \cos \theta_R \quad (\text{B17.26})$$

$$\frac{c}{g+a} = \frac{x'}{b}; \quad \frac{x'}{b} = -\frac{x \cdot \cos \theta_R}{g+x \cdot \sin \theta_R}; \quad x = \frac{x' \cdot g}{(b \cdot \cos \theta_R - x' \cdot \sin \theta_R)} \quad (\text{B17.27})$$

$$\frac{g'}{g+a} = \frac{b'}{b}; \quad g' = \frac{(g+a)b'}{b} \quad (\text{B17.28})$$



$$y = y' \frac{g'}{b'} = y' \frac{(g+a)}{b} = y' \frac{(g+x \cdot \sin \theta_R)}{b} \quad (\text{B17.29})$$

$$y = y' \frac{g \cdot \cos \theta_R}{(b \cdot \cos \theta_R - x' \cdot \sin \theta_R)} \quad (\text{B17.30})$$

we obtain the relations in Equations (B17.21) and (B17.22). Solving for the location on the detector array, x' and y' :

$$x' = x \frac{b \cdot \cos \theta_R}{(g+x \cdot \sin \theta_R)} \quad (\text{B17.31})$$

$$y' = y \frac{(b \cdot \cos \theta_R - x' \cdot \sin \theta_R)}{g \cdot \cos \theta_R} \quad (\text{B17.32})$$

B17.3.4 Difference Angle

For each area element, $d_A(x, y)$ on the DUT at location $P(x, y)$, the angular distance between the received ray direction, $\overrightarrow{PR}(x, y)$, and the specular ray direction, $\overrightarrow{PS^*}(x, y)$, is calculated.

Incoming ray
$$\overrightarrow{SP} = \vec{P} - \vec{S} = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} - \begin{bmatrix} x_S \\ 0 \\ d_S \end{bmatrix} = \begin{bmatrix} x - x_S \\ y \\ -d_S \end{bmatrix} = |\overrightarrow{SP}| \cdot \begin{bmatrix} \sin \theta_i \cos \phi_i \\ \sin \theta_i \sin \phi_i \\ \cos \theta_i \end{bmatrix} \quad (\text{B17.33})$$

Specular ray
$$\overrightarrow{PS^*} = \vec{S^*} - \vec{P} = \begin{bmatrix} 2x - x_S \\ 2y \\ d_S \end{bmatrix} - \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} = \begin{bmatrix} x - x_S \\ y \\ d_S \end{bmatrix} = |\overrightarrow{PS^*}| \cdot \begin{bmatrix} \sin \theta_i \cos \phi_i \\ \sin \theta_i \sin \phi_i \\ -\cos \theta_i \end{bmatrix} \quad (\text{B17.34})$$

Received ray
$$\overrightarrow{PR} = \vec{R} - \vec{P} = \begin{bmatrix} x_R \\ 0 \\ d_R \end{bmatrix} - \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} = \begin{bmatrix} x_R - x \\ -y \\ d_R \end{bmatrix} = |\overrightarrow{PR}| \cdot \begin{bmatrix} \sin \theta_r \cos \phi_r \\ \sin \theta_r \sin \phi_r \\ \cos \theta_r \end{bmatrix} \quad (\text{B17.35})$$

$$\cos \theta^* = \frac{\overrightarrow{PR} \cdot \overrightarrow{PS^*}}{|\overrightarrow{PR}| |\overrightarrow{PS^*}|} = \frac{(x - x_S)(x_R - x) - y^2 + d_S d_R}{\sqrt{(x - x_S)^2 + y^2 + d_S^2} \sqrt{(x_R - x)^2 + y^2 + d_R^2}} \quad (\text{B17.36})$$

The specular ray direction for the case of reflection is identical to the transmissive case as long as x_S remains constant and $d_S = -d_S$, *i.e.*, when the point source is mirrored by the DUT. Thus, θ^* remains the same angle for reflection and transmission. Here, θ_i and ϕ_i are the inclination and azimuthal angles of incidence, respectively, and θ_r and ϕ_r are the angles of inclination and azimuth of the reflected and received light.

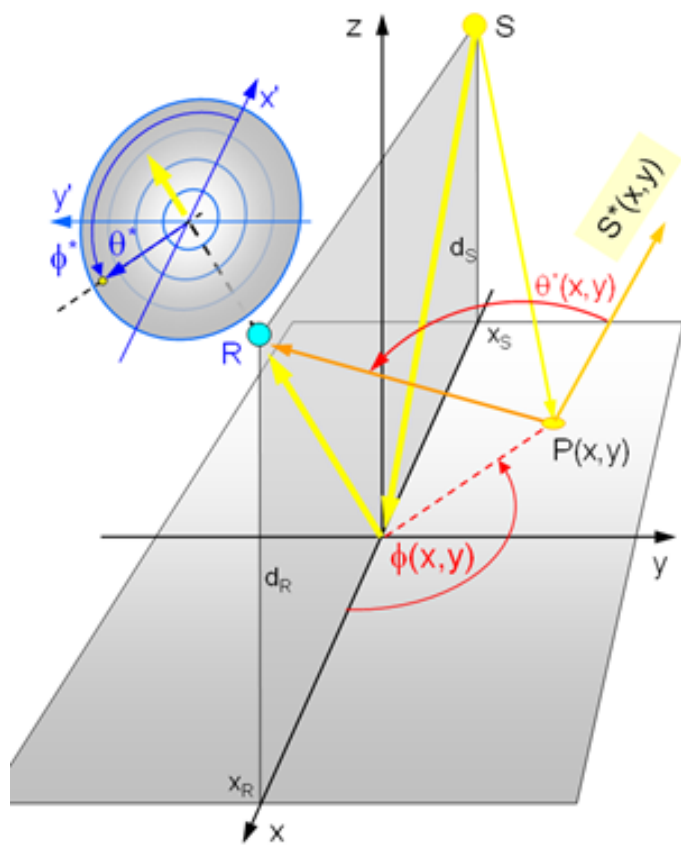


FIGURE B17.18. The new coordinate system on the LMD detector array with the difference angle, θ^* , and the corresponding azimuth angle ϕ^* .

B17.3.5 Relationship between ϕ (on DUT) and ϕ^* (on detector array)

The azimuth angle, ϕ^* , of the received beam $\overrightarrow{P(x,y)R}$ in the coordinate system of the LMD detector array is obtained with the equations that specify the imaging, (B17.21) and (B17.22), as follows:

$$\tan \phi(x, y) = \left(\frac{y}{x} \right); \quad \tan \phi^*(x', y') = \left(\frac{y'}{x'} \right) \quad (\text{B17.37})$$

with

$$x' = x \frac{b \cdot \cos \theta_R}{(g + x \cdot \sin \theta_R)}, \quad \text{and} \quad y' = y \frac{(b \cdot \cos \theta_R - x' \cdot \sin \theta_R)}{g \cdot \cos \theta_R} \quad (\text{B17.38})$$

$$\tan \phi^* = \left(\frac{y'}{x'} \right) = \left(\frac{y(b \cdot \cos \theta_R - x' \cdot \sin \theta_R)(g + x \cdot \sin \theta_R)}{x(b \cdot \cos \theta_R)(g \cdot \cos \theta_R)} \right) \quad (\text{B17.39})$$

$$\tan \phi^* = \frac{y}{x} \cdot \frac{\left(b \cdot \cos \theta_R - x \frac{b \cdot \cos \theta_R}{(g + x \cdot \sin \theta_R)} \sin \theta_R \right) (g + x \cdot \sin \theta_R)}{(b \cdot \cos \theta_R)(g \cdot \cos \theta_R)} \quad (\text{B17.40})$$

which can be simplified to



$$\tan \phi^* = \frac{y}{x} \cdot \frac{\left(1 - x \frac{\sin \theta_R}{(g + x \cdot \sin \theta_R)}\right) (g + x \cdot \sin \theta_R)}{g \cdot \cos \theta_R} \quad (\text{B17.41})$$

$$\tan \phi^* = \frac{y}{x} \cdot \frac{(g - x \cdot \sin \theta_R + x \cdot \sin \theta_R)}{g \cdot \cos \theta_R} = \frac{y}{x \cdot \cos \theta_R} = \frac{\tan \phi}{\cos \theta_R} \quad (\text{B17.42})$$

yielding

$$\phi^* = \tan^{-1} \frac{y}{x \cdot \cos \theta_R} = \tan^{-1} \frac{\tan \phi}{\cos \theta_R} \quad (\text{B17.43})$$

B17.3.6 Variation of Illuminance Across the DUT Surface, $E(x, y)$

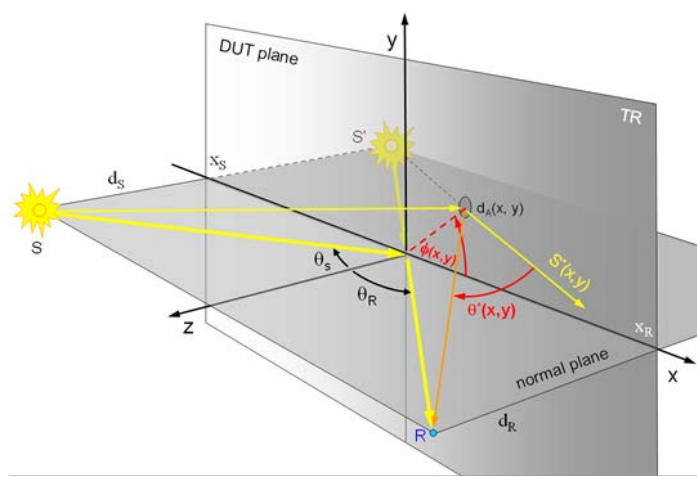


FIGURE B17.19. Geometric relations for evaluation of the illuminance across the DUT surface.

With the incoming ray

$$\vec{r} = \vec{P} - \vec{S} = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} - \begin{bmatrix} x_S \\ 0 \\ d_S \end{bmatrix} = \begin{bmatrix} x - x_S \\ y \\ -d_S \end{bmatrix} = \begin{bmatrix} \sin \theta_i \cos \phi_i \\ \sin \theta_i \sin \phi_i \\ \cos \theta_i \end{bmatrix} \quad (\text{B17.44})$$

its length,

$$|\vec{r}| = \sqrt{(x - x_S)^2 + y^2 + d_S^2}$$

and the DUT surface normal,

$$\vec{n} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad (\text{B17.45})$$

the inclination angle of the incident beam, θ_i , is given by

$$\cos \theta_i = \frac{\vec{n} \cdot \vec{r}}{|\vec{n}| |\vec{r}|} = \frac{d_S}{\sqrt{(x - x_S)^2 + y^2 + d_S^2}} \quad (\text{B17.46})$$

Further,

$$E(x, y) = I \cdot \frac{\cos \theta_i}{|\vec{r}|^2} = I \cdot \frac{d_S}{\left(\sqrt{(x - x_S)^2 + y^2 + d_S^2}\right)^3}, \quad (\text{B17.47})$$



where I is the constant luminous intensity of the isotropic point light source. To obtain the BRDF/BTDF, the luminance of the reflected or transmitted light, $Y(x, y)$, is then divided by the illuminance $E(x, y)$. The following is a special case: $E(x_s, 0) = d_s^{-2}$.

B17.3.7 Fresnel Correction

Since each location on the DUT surface is illuminated from its own specific direction, the reflectance varies with the angle of incidence, θ_i , for perpendicular, (s), and for parallel, (p), polarization of the incident beam as follows:

$$R_s = \left| \frac{n_1 \cdot \cos \theta_i - n_2 \cdot \cos \theta_t}{n_1 \cdot \cos \theta_i + n_2 \cdot \cos \theta_t} \right|^2 = \left| \frac{n_1 \cdot \cos \theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \cdot \sin \theta_i\right)^2}}{n_1 \cdot \cos \theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \cdot \sin \theta_i\right)^2}} \right|^2 \quad (\text{B17.48})$$

$$R_p = \left| \frac{n_1 \cdot \cos \theta_t - n_2 \cdot \cos \theta_i}{n_1 \cdot \cos \theta_t + n_2 \cdot \cos \theta_i} \right|^2 = \left| \frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \cdot \sin \theta_i\right)^2} - n_2 \cdot \cos \theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \cdot \sin \theta_i\right)^2} + n_2 \cdot \cos \theta_i} \right|^2 \quad (\text{B17.49})$$

where n_1 and n_2 are the refractive indices of the incidence (usually air with $n_1 = 1$) and reflecting medium, respectively. The reflectance for unpolarized light is given by the average of R_s and R_p . With $n_2 = 1.5$, the reflectance is 4 % for normal incidence. At 30° angle of inclination the reflectance increases to 4.152 %, *i.e.*, a change by a factor 1.03807. The equations (B17.48) and (B17.49) above can be used to compensate for the effect of increasing reflectance in the specular direction with angle of light incidence, $\theta_i(x, y)$.

B17.3.8 Bringing Them All Together

From the measured luminance distribution on the detector array, $L(x', y')$ or in the tristimulus case the combination of $X(x', y')$, $Y(x', y')$ and $Z(x', y')$ and with the equations defining the imaging of the DUT to the LMD detector array, (B17.21) and (B17.22), we obtain the reflected luminance at each location, (x, y) on the DUT, and with Eq. (B17.47) we get the illuminance at these locations. With Eqs. (B17.36) and (B17.43) we obtain the spherical angles θ^* and ϕ^* at each DUT location (x, y) .

The quotient,

$$f_{\text{BSDF}}(\theta^*(x, y), \phi^*(x, y)) = \frac{L(x, y)}{E(x, y)} \quad (\text{B17.50})$$

is the BSDF.

Starting with the *equally* spaced grid of BSDF-data obtained from the elements of the LMD detector array, we obtain a *grid with variable spacing* on the DUT plane. For each of the elements of that grid we calculate the pair of angles θ^* and ϕ^* and the corresponding cartesian coordinates x^* and y^* , according to Eqn. (B17.51), which again is from a *grid of BSDF-data elements with varying spacing*. From the latter grid we obtain a grid with constant spacing in x^* and y^* by interpolation and re-sampling. A typical result is shown in FIGURE B17.20. The cartesian coordinates of $f_{\text{BSDF}}(\theta^*(x, y), \phi^*(x, y))$, x^* and y^* are given as:

$$x^* = \theta^* \cdot \cos \phi^*; \quad y^* = \theta^* \cdot \sin \phi^* \quad (\text{B17.51})$$

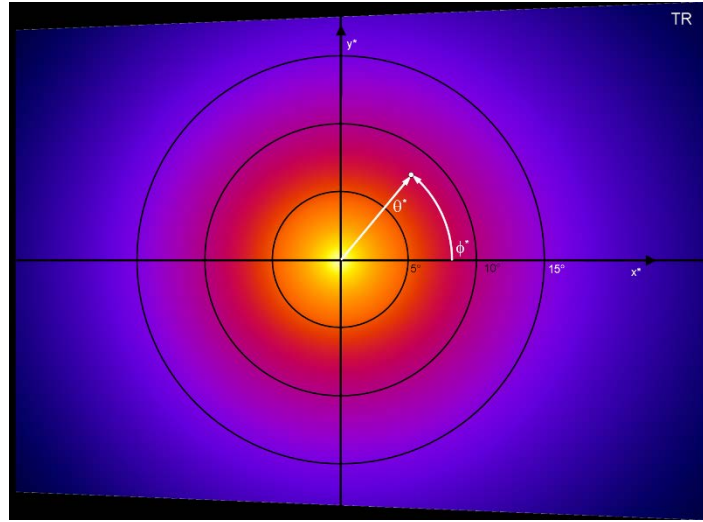


FIGURE B17.20. BSDF representation in a polar coordinate system centered about the specular (regular) peak of reflection or transmission.

B17.3.9 Special Case - In-Plane Variations

When we are only considering light rays in the xz -plane that contains the light source, S , and the receiver aperture, R , and with $y = 0$, Eq. (B17.36) reduces to

$$\cos \theta^*(x) = \frac{(x - x_S)(x_R - x) + d_S d_R}{\sqrt{(x - x_S)^2 + d_S^2} \sqrt{(x_R - x)^2 + d_R^2}} \quad (\text{B17.52})$$

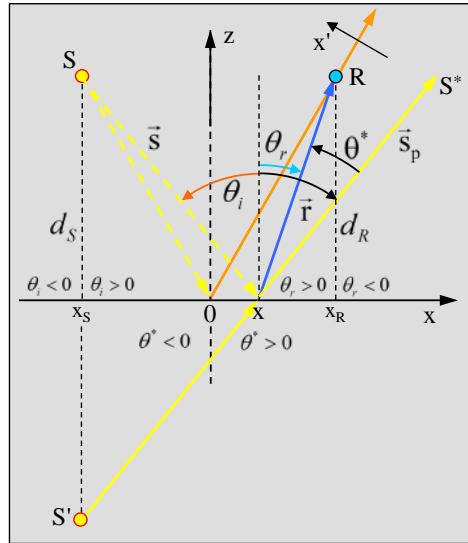


FIGURE B17.21. In-plane geometry with sign conventions for θ_i , θ_r , and θ^* .



Using the following relations:

$$\sin \theta_r(x) = \frac{(x_R - x)}{\sqrt{(x_R - x)^2 + d_R^2}}; \sin \theta_i(x) = \frac{(x - x_S)}{\sqrt{(x - x_S)^2 + d_S^2}} \quad (\text{B17.53})$$

or

$$\cos \theta_r(x) = \frac{d_R}{\sqrt{(x_R - x)^2 + d_R^2}}; \cos \theta_i(x) = \frac{d_S}{\sqrt{(x - x_S)^2 + d_S^2}} \quad (\text{B17.54})$$

we finally obtain

$$\cos \theta^*(x) = \cos \theta_i \cdot \cos \theta_r + \sin \theta_i \cdot \sin \theta_r = \cos(\theta_i - \theta_r) = \cos(\theta_r - \theta_i) \quad (\text{B17.55})$$

and

$$\phi^* = \begin{cases} 0 & x > 0 \\ 180 & x < 0 \end{cases} \quad (\text{B17.56})$$

B17.3.10 Measured Quantities and Data Sets

In the general case, 2 objects are included in one measurement, each one represented by a data object (data set):

- Point light-source (isotropically emitting white or monochromatic light),
- Sample - DUT to be measured (transmissive and/or reflective).

Additionally, the illuminance of the DUT, $E(x, y)$, can be determined by measuring the reflected luminance of a *perfect reflecting diffuser* with reflectance ρ (also known as a *calibrated diffuse reflectance standard*). The illuminance $E(x, y)$ is obtained from the luminance of the light reflected by the reflectance standard, $L_{r\text{-std}}$, as:

$$E(x, y) = L_{r\text{-std}}(x, y) \frac{\pi}{\rho} \quad (\text{B17.57})$$

The luminance of the reflected light, $L_{r\text{-std}}$, is given as:

$$L_{r\text{-std}} = \frac{L_s \cdot A_s}{r^2} \cos \theta_i \cdot \frac{\rho}{\pi}, \quad (\text{B17.58})$$

where L_s is the source luminance, A_s is the source emitting area, θ_i is the inclination angle, r the distance from the source to measured surface element. With a light source area of $2 \times 2 \text{ mm}^2$, *e.g.*, an LED with phosphor coating, and a distance to the DUT of 500 mm, $L_{r\text{-std}} \div L_s$ for normal incidence is about 5×10^{-6} .

The isotropically emitting point light source provides illuminance for the DUT and the reference luminance level for transmittance and reflectance (see FIGURE B17.22). From the measured PSF of the light source, the system signature can be obtained, *i.e.*, highest directional resolution including scattering of the LMD optics and the LMD stray light level. The *source luminance* is taken as reference for determination of the reflectance and transmittance ratio in the regular direction, R_s and T_s , respectively. The *source chromaticity* is taken as reference for determination of the shift in chromaticity induced by scattering. Usually, short wavelengths are scattered more strongly, so the light reflected in the specular direction undergoes a shift to the red part of the spectrum. This red shift is often distinctly visible in transmissive scattering samples.

Luminance of light source
Chromaticity of light source

reference for reflectance/transmittance in the specular/regular direction
 reference for directional variations of chromaticity induced by scattering

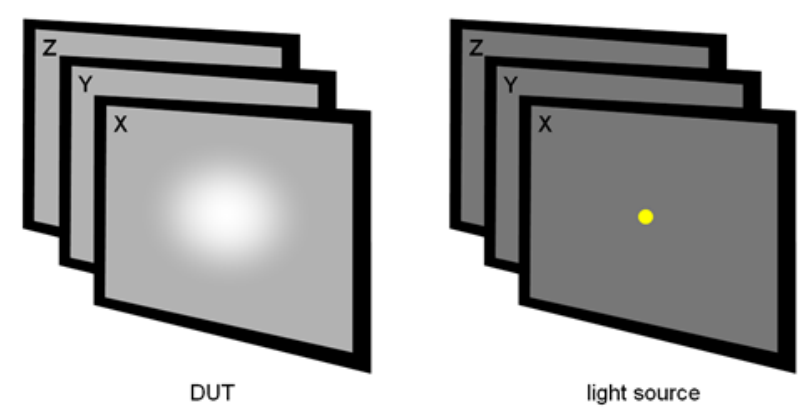


FIGURE B17.22. Typical tristimulus records (*i.e.*, images of the PSF) for the DUT and the light source.

APPLICATIONS

- Characterization of micro-structured scattering anti-glare (AG) coatings and layers (glass, polymer films) [B17.18]
- Characterization of the reflectance of electronic displays, separation of mirror, haze and Lambertian components

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B18 DIGITAL FILTERING BY MOVING-WINDOW AVERAGE

Purpose: The purpose of this discussion is to describe a simple method of performing low pass filtering and band stop filtering by a digital moving window average filter (MWAF, also known as a running average), and to describe some benefits and limitations of this approach.

Measurements such as § 10.2.2 Response Time collect multiple discrete luminance values over time, and then examine the resulting luminance/time waveform for features such as maximums and minimums. The uncertainty and repeatability of this feature analysis can often be improved by filtering out sample to sample noise (low pass filtering) or by filtering out superimposed periodic “ripple” (band stop/notch filtering).

The purpose of this discussion is to describe a simple method of performing low pass filtering and band stop filtering by a digital moving window average filter (MWAF, also known as a running average, see glossary), and to describe some benefits and limitations of this approach. Note that there are better noise and band pass filters to be found in any book on digital filtering, and that this discussion is not intended to preclude or discourage the use of such filters. The use of the MWAF is proposed for the purposes of this specification for the following reasons:

1. The MWAF is one of the simplest digital filters, and is therefore relatively easy to implement, especially in limited programming environments such as spreadsheets.
2. The simplicity of the MWAF also means that there is less risk of having a measurement corrupted by a bug in the digital filter, since the MWAF is relatively easy to validate by hand.
3. The MWAF is one of the filters most likely to be found pre-installed in equipment such as digital storage oscilloscopes.
4. The MWAF, when used within the constraints listed below, yields results very close to the results of more sophisticated filters.
5. The MWAF, when compared to more sophisticated filters, often yields smoother waveforms at maximums and minimums, making measurements based on maximums and minimums easier and more reproducible.
6. The MWAF, when used as a ripple filter, filters out any periodic ripple waveform, including the sawtooth waveform and other more complex waveforms characteristic of FPD refresh.

Definitions:

SampleRate = rate at which samples are collected, in samples/second

SampleCount = number of samples collected.

RawData[0...SampleCount-1] = Input array of raw data samples

FilteredData[0...SampleCount-1] = Output array of filtered data samples.

FilterPeriod = period of ripple to filter out (see discussion below).

MovingWindowAverageFilter:

In order to be clear on just how the MWAF can be accomplished, the following is a simple hypothetical pseudo-code computer program to perform the MWAF:

```

FilterCount = NearestInteger(FilterPeriod / SampleRate)
FC2 = FloorInteger(FilterCount/2)
for I = FC2 TO SampleCount-(Filtercount-FC2)
{
    Sum = 0
    for J = (I - FC2) TO (I - FC2 + FilterCount -1)
        Sum = Sum + RawData[J]
    FilteredData[I] = Sum / FilterCount
}

```

Each element in the FilteredData output array is set to the average of the FilterCount elements in the RawData input array centered on the current index (I). Note that when FilterCount is an even number, the resulting FilteredData is time shifted by SampleRate/2 toward the origin. Odd values of FilterCount do not exhibit this time shift.

The filtered average is not computed in cases where the moving average window would extend outside the RawData array, as this would result in less filtering near the beginning and end of FilteredData (this causes problems in ripple filters, since the ripple is not fully suppressed at the beginning/end of FilteredData). If desired, the uncomputed elements at the beginning/end of FilteredData may be extrapolated by being set to the first/last computed elements, respectively.

Noise Filter:



The moving average filter may be used as a sample-to-sample noise (or low pass) filter. In this application, FilterPeriod should be a small fraction (typically $\leq 10\%$) of the measured quantity. For example, when measuring a rise time of 20.0 ms, the FilterPeriod should be 2.0 ms or less to avoid excessive smoothing of the waveform to be measured.

Ripple Filter:

The moving average may also be used as a crude band-stop filter to filter out a recurring periodic waveform (ripple) superimposed on top of the waveform of interest. For example, an LCD frame refresh waveform with a period of 16.6 ms may be superimposed on top of a 120.0 ms turn-on waveform. In this application, FilterPeriod should be set equal to the ripple period. When correctly applied, this filter can greatly reduce the superimposed ripple. The filter may be applied multiple times to block out multiple ripple waveforms with different periods.

Some limitations of this approach:

FilterPeriod should equal the ripple period as accurately as possible.

FilterCount should be as large as possible (at least 10, preferably > 20). This can be accomplished by increasing SampleRate, or by setting FilterPeriod to an integer multiple of the ripple period (but only in cases where the ripple amplitude does not vary greatly during the resulting FilterPeriod). Another approach is to digitally resample the data to yield an higher SampleRate.

When FilterPeriod is similar to the measured quantity, the waveform of interest may itself be filtered enough to alter the measured quantity. For example, when filtering a 16.6 ms ripple waveform superimposed on top of a 25.0 ms turn-on waveform, the turn-on waveform might be smoothed enough so that the measured turn-on time is increased to 30.0 ms. This error may be acceptable, especially in cases where the turn-on time would be very difficult to measure due to the large superimposed ripple. Another approach would be to use a more sophisticated notch filter.



B19 COLLIMATED OPTICS

Purpose: We introduce you to a LMD that does not image the source. These devices place a detector at the position of the focal length of the lens (not at the focus of an image). The size of the detector and the focal length of the lens determine the angles of the rays of light that contribute to the measurement. Thus, the LMD may be placed close to the surface of the display yet not accept light from a wide angle of view.

A typical spot photometer uses imaged optics, where light is focused onto a sensor at an image plane located behind the focal point of the lens system. The image is formed beyond the focal point of the lens. With collimated optics, no image is formed and the sensing device (in this case a fiber optic cable attached to the LMD) is placed at the focal point of the lens. In this way the collimated optical system can scan a large area, be close to the area, and keep all measured rays of light staying within $\pm\theta_A$ of the optical axis.

In the imaged optics case, the diameter of the measurement area (D_M) is controlled by the angular field of view or aperture angle θ_A and measurement distance d as follows: $D_M = 2d \tan(\theta_A/2)$. For example, if $d = 500\text{mm}$ and $\theta_A = 2^\circ$, then $D_M = 17.4\text{mm}$. (Keep in mind that for these narrow angles $\theta_A \cong \tan \theta_A$ with θ_A in radians.)

In collimated optics systems, light is collected at the focal point, typically using a fiber optics cable. Since the fiber optics cable has a non-zero diameter, the system has a non-zero divergence angle θ_A , as opposed to a perfect “searchlight” beam illustrated by the dotted lines parallel to the optical axis above. This divergence angle, which is equivalent to the angular field of view (or aperture or subtense angle) for an imaged system, is controlled by the collimated optics lens geometry and by the fiber optics cable diameter.

In the collimated optics case, the diameter of the measurement area is controlled by the lens diameter D_L , the aperture angle θ_A , the focal length f , the diameter of the fiber D_F , and the measurement distance d as follows: $\theta_A = 2 \arctan(D_F/2f)$, and $D_M = D_L + 2d \tan(\theta_A/2)$. For example, if $D_L = 12.5\text{mm}$, $d = 100\text{mm}$, and $\theta_A = 1^\circ$, then $D_M = 14.2\text{mm}$.

Since a collimated optics system does not require focusing, it may be used either close to the display (as in a goniometer), or farther from the display (to facilitate reflectance measurements), as long as the resulting measurement area is appropriate to the measurement.

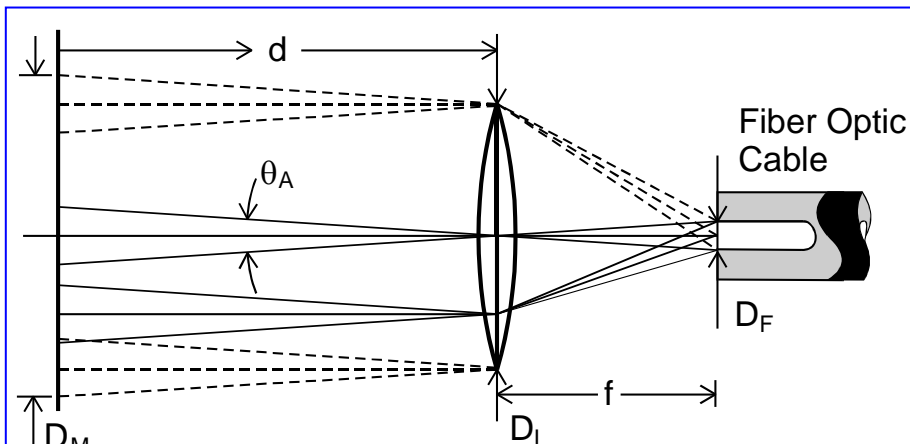


Fig. 1. Typical configuration using collimated optics.

B20 MEASURES OF CONTRAST—GRILLES AND MTFs

Abstract: The fidelity with which contrast is conveyed from an input pattern to the measured light on a display screen depends on the spatial variations of the pattern. This fidelity is commonly measured using one of two suites of input periodic patterns: black-and-white square waves of various spatial frequencies, and fully modulated sine waves of various spatial frequencies. For each pattern of either suite, a single number is reported, equivalent to the Michelson contrast

$(L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$. The square-wave inputs have the advantage of ease of production and measurement on a pixel-meshed screen. The sine-wave inputs have the advantage that they always generate sine-wave outputs if the transfer is linear and shift-invariant from input to output. Analysis methods based on both these suites (the latter of which is called the Modulation Transfer Function, or MTF, method) are explained in this tutorial.

1. MOTIVATION AND OVERVIEW

An optical system cannot accurately reproduce all of the spatial frequencies incident upon it. In particular, there is a maximum spatial frequency, known as the cutoff frequency, above which any input contrast is represented as zero output contrast. There is an inherent upper limit to the spatial-frequency spectrum in the case of a digital display; this limit is determined by the pixel spacing. No spatial-frequency information can be displayed whose pitch is less than the pixel spacing. Depending on the distance between the eye and the display, one or the other of these two factors limits the detail that can be discerned in the displayed image. If the eye is close enough to the screen to resolve the individual pixel elements, then clearly the pixel spacing determines the resolution limit. If the eye is too far away from the display to resolve individual



pixels, then the limiting factor is the eye. For purposes of this tutorial, only the behavior of the display will be considered; the eye will be ignored.

How can one quantify the contrast performance of a digital display system? One sensible choice is to measure the optical transfer function (OTF), a choice that has long proven to be a very good way of characterizing high-quality optical systems. The OTF is a measure of how the contrast in an object is transferred to an image formed by an optical system, e.g., from the display to the retina in the eye. The underlying construction is to decompose (linearly, in two dimensions) the input object and output image into a Fourier series of sine and cosine waves of different spatial frequencies. Given the assumption that an optical system effects a linear transfer from object to image (and also a bit more, as will be explained in Section 3 below), all the frequency components in the input object are separately scaled in traversing the optical system, and then recombined (superposed) to produce the output image. Although the OTF is a complex function, with both real and imaginary parts, only its modulus is significant in analyzing most flat panel displays. When the blur incurred by the optics is symmetric (as is typically the case), the phase portion of the OTF can be ignored. The modulus of the OTF is typically referred to as the modulation transfer function (MTF).

A computer display can be analyzed in terms of the MTF, just as pure optical systems can. However, it must be remembered that there are differences between the traditional optical concepts and those that are operative in the digital display. One obvious difference is that the display is not purely optical but turns electrically induced input patterns to light outputs. Assuming that compensation has been made for point nonlinearities (such as gamma in a CRT), the main consequence of this fact is that, whereas light from the optical system is a continuous (analog) field, the light from a computer (flat-panel) display is more accurately represented as discrete (digital) picture elements. Hence, sine waves are not a natural representation of the digital image, even though they are convenient to manipulate using the MTF formalism. A case can be made, therefore, for using an alternative to the MTF, replacing input sine waves with square-wave patterns. This alternative is called the grille method. Rather than try to canonize the MTF or the grille method as the correct way to assess the contrast of a display as a function of spatial frequency, this tutorial discusses both methods in a common context.

Both the MTF and the grille method use the concept of spatial frequency. The former expresses the spatial frequency of a one-dimensional sine-wave test pattern through the number of cycles per millimeter; the latter expresses spatial frequency through the number of line pairs per millimeter (lp/mm), where a line pair consists of a light line next to a dark line (both having the same width). In either representation, the spatial-frequency spectrum is continuous and varies from the equivalent of “dc” to frequencies up to several thousand line pairs (or cycles) per millimeter. As the frequency increases, the MTF, and also the grille contrast response, typically decrease: the blur incurred by the optical system affects fine detail more than it affects coarse image features. To convey the further commonality of the MTF and grille methods, we first review the grille method, and then proceed to the details of the MTF.

2. THE GRILLE METHOD OF QUANTIFYING CONTRAST

The grille method probes a display with several input patterns (grilles) of varying fineness, each grille being uniform in one dimension and a square wave in the perpendicular dimension. This geometry can also be described as a periodic series of bright and dark lines, usually of equal width. Fineness (spatial frequency) is defined as “line pairs per millimeter” or “line pairs per (angular) degree.”¹ This is analogous to temporal frequency (Hertz) except that distance or angle is used instead of time. In the case of a computer display, a screen that is entirely one gray level would have a spatial frequency of zero.² When the display has a series of black and white bars, each approximately 25 mm (1 in) wide, then the spatial frequency is 0.04 lines per millimeter or 0.02 line pairs per millimeter. If there are about 25 pairs of black and white lines in 25 mm, then the spatial frequency would be 1 line pair per mm.

For each spatial frequency of the input square wave, a single number is measured on the output pattern (which is no longer a square wave) that represents the contrast of that output wave. This number is referred to as the Michelson contrast (Boynnton, 1966), defined as

$$C_m = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$

where L_{\max} is the maximum luminance from the brightest portion of the image, and L_{\min} is the minimum luminance from the dimmest portion of the image. The Michelson contrast has a range of values between zero and one. Suppose one value of Michelson contrast is measured for each spatial frequency of input grille. Each such number is called a *grille contrast*, and

¹ These two measures are essentially the same. The selection of which one is used depends on the geometry of the situation. If the spatial frequency is measured on a display, it may be convenient to measure the periodic pattern in terms of lines per millimeter. On the other hand, if one is looking at a target, then the distance between the eye and the target will affect the spatial frequency and then the angular metric may be more appropriate.

² Strictly speaking, such a display will have a “zero” or “dc” spatial frequency of the reciprocal of the width or height of the display.



the set of such numbers might be called a grille contrast function, in analogy with the MTF. Unlike the MTF, however, the grille contrast does not convey all the information about the grille distortion in passing from input to output.

An alternative, yet equivalent, performance metric to C_m is the contrast ratio C , defined as

$$C = \frac{L_{\max}}{L_{\min}}.$$

The value of C (equivalent to C_G in § 7.2 or C_{seq} in § 5.10) can be quite large, since the denominator can become small for a very good display in a dark room. Michelson contrast and contrast ratio are related to one another as follows:

$$C_m = \frac{C-1}{C+1} \quad \text{and} \quad C = \frac{1+C_m}{1-C_m}.$$

It should be noted that C_m is traditionally used to characterize CRT displays, so the use of C_m would facilitate comparisons of FPDs and CRTs. However, note that C_m is relatively insensitive to comparisons involving high contrasts. If there is some ambient light that is reflected or scattered towards the user, then L_{\min} will not be zero and the Michelson contrast will never reach 100 %. Of course, in a dark room, there will be essentially no ambient light and the Michelson contrast would be expected to be able to approach unity.

These remarks illustrate the different representations of contrast that are equivalent to the Michelson contrast. However, the Michelson contrast itself has a distinguished status among all these representations, because it is precisely what is evaluated in MTF analysis (albeit for different input patterns). This will be clear in Section 3.

3. THE MODULATION TRANSFER FUNCTION

The following introduces the MTF in general terms; the application of the MTF in a CRT-measurement context is more fully discussed in EIA (1990) and can be carried over directly to flat-panel displays.

3-1. Representing linear systems by convolutions

In order for a linear system to have a defined MTF, it must be *shift-invariant*, i.e., the outputs associated with a given input (in space or time) must not depend on the space or time at which a given input is delivered. Furthermore, the attribute of linearity means that (i) if input I produces output I' , then a scaled version of the input kI produces output kI' ; and (ii) if input I_1 produces output I'_1 , and input I_2 produces output I'_2 , then input $I_1 + I_2$ produces output $I'_1 + I'_2$. These properties can be shown to imply that the operation of the linear device can be represented as a convolution on the input to produce the output.

In two spatial dimensions,

$$I'(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} T(x', y') I(x - x', y - y') dx' dy' \equiv T(x, y) * I(x, y) \quad (1)$$

where $T(x, y)$ is called the *point-spread function* of the system, and the star denotes convolution. Although $T(x, y)$ characterizes the system independent of the inputs and outputs, the function $T(x, y)$ can be measured by using a unit point of input (the delta function, whose value is zero except at one spatial location, and whose integral over all x - y space is 1), and recording the value $I'(x, y)$ at all output times. Hence the name point-spread function.

In one spatial dimension,

$$I'(x) = \int_{-\infty}^{\infty} T(x') I(x - x') dx' \equiv T(x) * I(x), \quad (2)$$

where $T(x)$ is called the *line-spread function* of the system. Although $T(x)$ characterizes the system independent of the inputs and outputs, the function $T(x)$ can be measured by using as input a unit line impulse in space (the delta function, whose value is zero except at one value of x , and whose integral over all x is 1), and recording the value $I'(x)$ at all output times. Hence the name line-spread function. It is assumed here that, on the screen, the y dependence of I and I' does not exist or has been averaged out. Characterizing a two-dimensional optical system with a one-dimensional test pattern such as a line is also permissible if the system is *isotropic*, i.e., the direction of the line does not matter.

The term "modulation transfer function" is used in conjunction with systems in one spatial dimension (as in Eq. 2, or for isotropic two-dimensional systems completely characterized by a line-spread function independent of direction. However, the term does not apply to full two-dimensional spatial systems (as in Eq. 1). Therefore, this tutorial will deal only with Eq. 2.

3-2. Defining the MTF using the Fourier Transform

As will be shown in this section, when a cosine wave is input into a shift-invariant spatial system, it results in an output that is a shifted and scaled (attenuated) replica of the input. For a system with a symmetric line-spread function (such as characterizes most optical systems), the spatial shift is zero, and the MTF is defined as the ratio of attenuation as a function of the spatial frequency of the input wave to the attenuation of dc (zero-frequency).



For one spatial dimension, a unit-amplitude cosine wave with spatial frequency f (perhaps in cycles per visual degree, or cycles per centimeter of screen width) is

$$\begin{aligned}
 I'_c(x) &= \int_{-\infty}^{\infty} T(x') \cos[2\pi f(x - x')] dx' \\
 &= \cos(2\pi fx) \int_{-\infty}^{\infty} T(x') \cos(2\pi fx') dx' + \sin(2\pi fx) \int_{-\infty}^{\infty} T(x') \sin(2\pi fx') dx' \\
 &\equiv A(f) \cos(2\pi fx) - B(f) \sin(2\pi fx) \\
 &\equiv |M(f)| \cos(2\pi fx - \phi).
 \end{aligned} \tag{3}$$

In the third line of Eq. (3),

$$A(f) = \int_{-\infty}^{\infty} T(x') \cos(2\pi fx') dx' \tag{4}$$

and

$$B(f) = - \int_{-\infty}^{\infty} T(x') \sin(2\pi fx') dx' \tag{5}$$

are the real and imaginary parts of the Fourier transform of $T(x)$ (see Bracewell, 1978). In full, this Fourier transform is given by

$$\begin{aligned}
 M(f) &= A(f) + j B(f) \\
 &= \int_{-\infty}^{\infty} T(x') \exp(-j2\pi fx') dx' ,
 \end{aligned} \tag{6}$$

where $j = \sqrt{-1}$. In the fourth line of Eq. (3),

$$|M(f)| = [A(f)^2 + B(f)^2]^{1/2} \tag{7}$$

is the modulus of $M(f)$, and

$$\phi = \arctan[B(f)/A(f)] \tag{8}$$

is the phase of the Fourier transform.

Equations (3)-(8) show that a shift-invariant linear system incurs a very simple transformation on an input cosine (or sine) wave: the output is an attenuated, phase-shifted replica of the input. The attenuation factor is given by $|M(f)|$, and the phase shift (in radians) is given by ϕ .

In general, the function $M(f)$ is called the *optical transfer function* of the system whose line-spread function is $T(x)$. However, if $T(x)$ is symmetric [that is, if $T(x) = T(-x)$ for all x], then $B(f) = 0$, $M(f) = A(f)$ is a real function, and $M(f)/M(0)$ is in that event called the *modulation transfer function* (MTF) of the spatial system. This particular usage—for the optical domain, and in particular to characterize lenses and human visual sensitivity—is documented by Cornsweet (1970) and by Wandell (1995). It should be appreciated that the symmetry of $T(x)$ is a good assumption for a flat-panel display, so this restriction does not impair the usefulness of the MTF.

The derivation of the term "modulation transfer function" becomes clear in the optical context when one remembers that light cannot have negative intensity, hence one actually measures an optical system with the fully modulated cosine wave $1 + \cos(2\pi fx)$ rather than with $\cos(2\pi fx)$. The output from this waveform is $M(0)[1 + m \cos(2\pi fx)]$, where m is the modulation depth of the waveform associated with frequency f . The factor m is, in fact, the MTF $M(f)/M(0)$ evaluated at frequency f .

3-3. Useful properties of the MTF

As can be seen from Section 3-2, in one spatial dimension with a symmetric line-spread function, the MTF is the (real) Fourier transform of the line-spread function, normalized so the dc value is 1. In the Fourier domain, Eqs. (1) and (2) become particularly simple, due to the *convolution theorem* (see Bracewell, 1978):

$$\text{If } I'(t) = T(t) * I(t), \text{ then } I'(f) = T(f)I(f). \tag{9}$$

Here, $I(f)$, $T(f)$, and $I'(f)$ the respective Fourier transforms of $I(t)$, $T(t)$, and $I'(t)$. Hence, in the Fourier-transform domain, a convolution between two functions becomes represented as a simple multiplication, frequency-by-frequency. In performing



digital simulations of shift-invariant linear systems (optical or electrical), the convolution theorem becomes especially useful for two reasons:

- (a) There may be reason to perform multiple convolutions, which are expensive computationally; and
- (b) There is a method of performing the Fourier transform that is very efficient: The Fast Fourier Transform, developed by Cooley and Tukey in 1965 (see Bracewell, 1978).

These rather formal considerations are closely related to an informational advantage of the MTF over the grille contrast function (described in Section 2). To understand that advantage, it is helpful first to realize that the MTF and the grille-contrast function are measured the same way but using different input patterns: each point of the MTF is a Michelson contrast, this time measured using fully modulated *sine*-wave inputs instead of square-wave inputs. To see this, imagine a fully modulated input sine wave

$$I(x) = A[1 + \cos(2\pi fx)]. \quad (10)$$

Using the property that sine waves are at most scaled by a linear, shift-invariant system with a symmetric line-spread function, we can now write the following expression for the output sine wave:

$$L(x) = A[a + b \cos(2\pi fx)]. \quad (11)$$

The Michelson contrast of this output function is then $(L_{\max} - L_{\min})/(L_{\max} + L_{\min})$, which in this case is

$$C_m = 2b/(2a) = b/a. \quad (12)$$

But the MTF of the system is the ratio of the Fourier transform of Eq. (11) at frequency f , divided by the Fourier transform of Eq. (11) at frequency 0. The numerator is $Ab/2$, and the denominator is the mean of $L(x)$, which is simply Aa . The ratio of numerator and denominator is just $b/(2a) = C_m/2$. This shows how the MTF is composed of a set of (half-scaled) Michelson-contrast measurements on input patterns that are fully modulated sine waves.

4. COMPARATIVE APPLICABILITY OF GRILLE CONTRAST AND MTF

From Sections 2 and 3, it can be seen that, although the MTF and the grille contrast function have much in common, there are differences that seem to confer an informational advantage to the MTF. Given the spatial frequency of an input sine wave and the Michelson contrast of the output wave, one knows the shape of the output wave (it is another sine wave). A series of such contrast measurements at various spatial frequencies is therefore enough to predict the response to any input, so long as the assumptions in Sections 1 and 3 are satisfied. However, the grille contrast for a square-wave input pattern does not convey all the information about the output distortions of arbitrary input patterns.

The apparent informational advantage of the MTF over the grille contrast function is largely illusory in real-world applications, because the assumptions of shift-invariance, and even of linearity, do not apply to real displays. For example, the spatial output spread of an input line varies from place to place on a display screen, contrary to the assumption of shift-invariance. Because the main effect of input-to-output spreading occurs at high spatial frequencies, one could imagine measuring local parts of the screen with sine waves to effect a sort of “local MTF” characterization, complete with its power to predict contrast loss for arbitrary patterns. However, there would still remain the problem that the output line shape (e.g., the CRT beam shape) is highly nonlinear in peak input (e.g., the CRT beam current). This is quite apart from the gamma nonlinearity, which is presumed compensated on the input. Because the input sine wave has a large dynamic range (from black to white), one cannot hope to achieve even approximate linearity for an MTF interpretation.

Given these unpleasant facts of the real world, the apparent advantage of the MTF must bow to the more relevant advantage of the grille-contrast function: ease and repeatability of measurement. Because grille contrast measurements reveal contrast losses only at the highest spatial frequencies (at which sine waves are represented as approximate square waves anyway), the grille-contrast function might be roughly imagined to be as close as one could get to an MTF. However, the rough analogy should not blind one to the essential nonlinearity of the system one is measuring.

In summary, the grille-contrast function is to be recommended over the MTF for display measurement, partly because the measurements are more easily and repeatably performed, and partly because there is less tendency to import linear-system concepts where they do not belong.

5. EFFECTS OF VIEWING ENVIRONMENTS ON CONTRAST FUNCTIONS

Contrasts on a displayed image in a dark room will always be greater than that in an environment with ambient lighting. This is so because veiling reflection from the ambient increases the minimum light levels from the image in greater proportion than it increases the maximum light levels from that same image. Accordingly, ambient light will decrease the components of the MTF (and also of the grille-contrast function) at nonzero spatial frequencies.

On the other hand, if there are internal reflections within the display unit itself, then the Michelson contrast with a bright screen image might not reach 100 % even in a dark room. For example, the light from a bright pixel could be reflected from one of the internal interfaces within the display and the reflected light could illuminate the adjacent pixel, thus reducing



contrast. The worst case is encountered in a well-lighted area or out of doors; in these cases, the perceived brightness of an unlit pixel case could appear quite bright. Not only do internal reflections contribute to the loss in contrast, but light scattered from a LCD layer, or from other internal components will also reduce the maximum contrast available in an operation environment. The reduction in contrast will be a function of spatial frequency, with the higher spatial frequencies likely to be affected the greatest.

6. GENERALIZATION TO TWO DIMENSIONS FORCED BY PIXEL GEOMETRIES

In a typical digital flat-panel display, neither the MTF nor the grille contrast function may be the same in different directions. If the pixels are non-square, these functions will be different in the horizontal and vertical directions. A still different contrast function will be measured when the spatial-frequency vector is oriented parallel to the diagonal of the image (even when the pixels are square). Thus, for a full characterization of the performance of a panel, an entire two-dimensional contrast function will be needed.

References for this MTF tutorial

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- [3] T. Cornsweet (1970), *Visual Perception*, Academic Press, pp. 312-330.
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B21 STATEMENTS OF UNCERTAINTY

Purpose: We attempt to familiarize you with the most recent vocabulary for describing the estimate of uncertainty in a measurement result.

Suppose we purchase a luminance meter for which the specifications state a $\pm 2\%$ “accuracy” with a “precision” of $\pm 0.1\%$. What do these terms mean? Is there a better way to express the uncertainties? There have been many terms used to describe measurement uncertainties: accuracy, inaccuracy, precision, imprecision, repeatability, reproducibility, variability, error, systematic error, random error, uncertainty, etc. All of these terms have been used in so many different ways that there has been a need to develop a precise terminology to deal with measurement uncertainties. Here we review some of the currently acceptable ways to describe measurement uncertainty, and we will do this using the example of photometric measurements. For a fuller discussion, see, for example, Barry N. Taylor and Chris E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition—this reference is based on the ISO *Guide to the Expression of Uncertainty in Measurement* (International Organization for Standardization), 1995. There is also an ANSI publication covering this material: ANSI/NCSL Z540-2-1997 *U.S. Guide to the Expression of Uncertainty in Measurement*, (American National Standards Institute/National Conference of Standards Laboratories), first edition, October 9, 1997. Also see the *International Vocabulary of Basic and General Terms in Metrology*, a joint publication from BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML (1993).

Consider a circular aperture light source with absolutely uniform luminance over the disc of light (this could be closely approximated using a large, well-designed integrating sphere with a small circular exit port and having a 99 % reflectance interior, for example). The specific quantity of interest subject to measurement is called the **measurand**, and in this case it is the luminance of the light source. Let’s assume that its luminance is exactly L_0 , i.e., the “true value” of the luminance is L_0 . This “true value,” which, in general, is unknown and unknowable, is the **value of the measurand**. The value of the measurand is the result we would obtain if everything were perfect—if the measurand were perfectly defined in the context of its use, and if a perfect instrument were used to determine its value (obviously such an instrument does not exist). What we are trying to do with our real laboratory instrumentation is to obtain a result that is as close as possible to the value of the measurand, and we want to know how comfortable we can be with that result, which is the purpose of the uncertainty statement.

Be aware of the difference between the error in a measurement and the uncertainty of a measurement. When we make a measurement there is an unknown and unknowable error and an uncertainty associated with the measurement. The error is how close the measurement result is to the value of the measurand, which we never know. The uncertainty refers to how unsure we are of the value of the measurand based on our measurement. Thus, we could accidentally have a very small error in our measurement result but yet have a large uncertainty associated with it. How do we establish the uncertainty? In what follows we will speak of quantities and relative quantities—like uncertainty and relative uncertainty. If we said the uncertainty in a 1 m measuring stick is 1 mm, we could also express the uncertainty as a relative uncertainty of 0.1 %, i.e., “relative” refers to the fractional amount of the quantity most often expressed as a percent.



With our luminance-meter example, the manufacturer claims an “accuracy” of $\pm 2\%$ with “precision” of $\pm 0.1\%$. How do we correctly interpret this? The claim most likely means: The luminance meter has a **relative uncertainty of measurement** at some level of confidence (e.g., 95 %) of 2 % with a **relative reproducibility** of 0.1 % over a 24 hour period, for example. The reproducibility suggests closeness of agreement between measurements made under different conditions, such as a few hours between measurements, using different operators, at different temperatures, etc. If the manufacturer meant that the 0.1 % applies when one makes repeated measurements over a short time trying to keep everything the same, the claim would be changed to state that the meter has a **relative repeatability** of 0.1 % over a ten-minute period, for example. With uncertainty statements there is usually a period of time over which the uncertainty estimate is regarded as reliable, for example, one month, six months, one year, etc., but we will ignore that for our purposes of illustration. The reported uncertainty of measurement (“accuracy”) for the manufacturer’s instrument should already include the reproducibility and/or the repeatability in its evaluation.

In the discussions here we are assuming that the results of the measurement of the measurand has a probability density function associated with it having a mean and a standard deviation that could only be obtained through an infinite number of measurements. The probability density function, its mean, and its standard deviation cannot be strictly known; they can only be estimated through repeated measurements. Thus, when we speak of a mean or a standard deviation from measurement results, we are always referring to an *estimate* of the mean and standard deviation of the probability density function. Often the probability density function is normal—also called Gaussian—but that is not necessarily always the case. See the references for further information.

Any measurement can have several contributions to its uncertainty. Each **component of uncertainty** u_i can be estimated by a standard deviation called the **standard uncertainty** u_i (equal to the square root of the estimated variance). Now, in general, there are two categories identified: **Type A evaluation of uncertainty** that refers to uncertainties that are evaluated by statistical means, and **Type B evaluation of uncertainty** that refers to uncertainties that are evaluated by other means. Type A uncertainty evaluation could be the standard deviation of the mean of a series of repeated observations, but it is not limited to such an evaluation. Type B uncertainty evaluation is based on scientific judgment accounting for all available relevant information, which can include manufacturer’s specifications, uncertainty in the calibration of the instrument, experience with the instrumentation, and so forth.

It may not be very obvious why there is a need for this new terminology. Let’s look at how we talked about uncertainty in the past: We used to consider that there were two types of measurement uncertainties. We called them “random uncertainties” and “systematic uncertainties,” a rather careless shorthand way of saying uncertainties arising from random effects (manifested by small random variations in the measurement result) and uncertainties arising from systematic effects (such as the calibration uncertainty of the instrument). With our above luminance-meter example, the “random uncertainty” would be obtained by making repeated measurements and calculating the standard deviation of those measurements—we would now call this the repeatability.

In the context of our document, we can illustrate the inadequacy of the terms “random uncertainty” and “systematic uncertainty.” Suppose we measure the luminance of a display as a function of voltage or gray-scale level, and we want to determine the best value of γ using the model $L = L_b + aV^\gamma$. We might use a nonlinear least squares technique to obtain γ and an estimation of its standard deviation σ_γ . That is not a “random uncertainty,” nor is it a “systematic uncertainty”; rather, it is a Type A uncertainty since it was derived from a statistical analysis of observations. In our earlier example of making a measurement of the luminance of the source, the Type A uncertainty is equivalent to the component of uncertainty arising from the observed random variations of our repeated observations (which in the past we would have called “random uncertainty”). For that same example, the Type B uncertainty is equivalent to the component of uncertainty arising from the quoted 2 % “accuracy” of the instrument (which in the past we would have called “systematic uncertainty”). However, Type A and Type B are not synonyms for “random” and “systematic.”

The **combined standard uncertainty** is the “root-sum-of-squares” (square root of the sum-of-the-squares, or RSS) of all the component uncertainties whether arising from a Type A evaluation or a Type B evaluation, $u = \sqrt{\sum u_i^2}$. Finally,

the **expanded uncertainty** is a **coverage factor** k times the combined standard uncertainty, or $U = ku$. The coverage factor increases the estimate of the uncertainty to reflect a higher probability that the unknown value of the measurand lies within the measurement result plus and minus the expanded uncertainty. Often, in the past, one would perhaps use $k = 2$ and say that the measurement had a “two-sigma” uncertainty. We would now say that the measurement has an expanded uncertainty of such-and-such with a coverage factor of $k = 2$. The coverage factor is not limited to being two, but it will depend upon the experiment.

Now, consider the above luminance meter for which the specifications state an “accuracy” of $\pm 2\%$ with a “precision” of $\pm 0.1\%$, which we will assume is its repeatability u_R . Suppose we are going to use it to measure the luminance of the exit port of an integrating sphere. Unless more detailed information were provided about the uncertainty statement, we would have to contact the manufacturer in order to know how the uncertainty estimate was established. We will assume that the manufacturer has already incorporated a coverage factor $k = 2$ in reporting the uncertainty of measurement of the



instrument. We will assume that this represents a 95 % confidence. [The manufacturer should have reported his uncertainty estimate by saying something such as: The instrument has a relative expanded uncertainty of 2 % with a coverage factor of two ($k = 2$) and a repeatability of 0.1 % over a ten-minute period.] Since the uncertainty is expressed in percent, we will call this relative expanded uncertainty $U_m/L = 2\%$, where L is the result of any luminance measurement. The instrument measurement uncertainty is one of the components of uncertainty that will be included in our estimating the uncertainty of our luminance measurement; it is a type B uncertainty estimate. Notice that when using the terminology involving uncertainty statements that the \pm is understood and does not need to be included.

Suppose we now obtain a series of ten measurement results of the exit port luminance and find the mean to be $L = 2314 \text{ cd/m}^2$ with a standard deviation of $u_r = 15.3 \text{ cd/m}^2$ (u_r is the repeatability of the measurement of the exit port luminance, not of the instrument); u_r is a type A uncertainty estimate. If u_r were only due to the repeatability of the instrument it would be approximately 2.3 cd/m^2 . The additional uncertainty must come from instabilities in the light source or in our method of making the measurement, e.g., if we were using a hand-held luminance meter, the additional uncertainty might come from our sloppy (and random) locating of our measurement at the center of a nonuniform exit port. Suppose that we are unaware of any other source of uncertainty in the measurement. We would have two components of uncertainty, the measurement uncertainty of the instrument and the repeatability uncertainty of the measurement of the exit port.

The expanded uncertainty with a coverage factor of two expresses a 95 % confidence that the measurand is within the expanded uncertainty of the measurement result. Our repeatability u_r of the luminance of the exit port is a single standard deviation representing a confidence of 68 %. What instrument uncertainty would we use, the expanded uncertainty (95 % confidence) or remove the coverage factor from the expanded uncertainty and use the combined standard uncertainty $u_m = U_m/2$ (68 % confidence)? It will depend upon our experience with the instrumentation, how stable it has proved to be, when it was calibrated, etc. The new combined standard uncertainty will be a RSS of the two components. The expanded uncertainty will be a coverage factor times the combined standard uncertainty.

Table 1. Uncertainty estimation of exit port luminance measurement example.

CSU = combined standard uncertainty; EUCF2 = expanded uncertainty with coverage factor of two ($k = 2$).
Instrument: u_r = repeatability (0.1 %); u_m = combined standard uncertainty (1 %); U_m = EUCF2 (2 %, $k = 2$).
Measured: u_r = measured repeatability of apparatus in use.

(A) = type A (B) = type B	Instrument is stable, reliable, recently calibrated: May want to use u_m .		No history of instrument reliability and stability, not recently calibrated: Use U_m .	
$L = 2314 \text{ cd/m}^2$	$u = \text{CSU}$	$u/L = \text{Relative CSU}$	$u = \text{CSU}$	$u/L = \text{Relative CSU}$
$u_r = 15.3 \text{ cd/m}^2$ (A) [but $u_r = 2.3 \text{ cd/m}^2$]	$u = \sqrt{u_m^2 + u_r^2}$	$\frac{u}{L} = \sqrt{\left(\frac{u_m}{L}\right)^2 + \left(\frac{u_r}{L}\right)^2}$	$u = \sqrt{U_m^2 + u_r^2}$	$\frac{u}{L} = \sqrt{\left(\frac{U_m}{L}\right)^2 + \left(\frac{u_r}{L}\right)^2}$
$U_m/L = 2\%$ (B)	$= 27.8 \text{ cd/m}^2$	$= 1.2\%$	$= 48.8 \text{ cd/m}^2$	$= 2.1\%$
$U_m = 46.3 \text{ cd/m}^2$ (B)	$U = \text{EUCF2}$	$U/L = \text{Relative EUCF2}$	$U = \text{EUCF2}$	$U/L = \text{Relative EUCF2}$
$u_m/L = U_m/2L = 1\%$ (B)				
$u_m = 23.1 \text{ cd/m}^2$ (B)	$= 55.4 \text{ cd/m}^2$	$= 2.4\%$	$= 97.5 \text{ cd/m}^2$	$= 4.2\%$

However, you determine the uncertainty of your measurement, it is important that you make that determination clear in the presentation of your results. Whether you used the manufacturer's combined standard uncertainty ($u_m = U_m/2$) or expanded uncertainty (U_m) in your calculation of the RSS combined standard uncertainty of your measurement, simply make it sufficiently clear so that any reader will be able to understand the origin of your uncertainty statement. Also, when reporting the uncertainty most will assume that you are reporting the expanded uncertainty with a $k = 2$ coverage factor. If that is not the case, it should be clearly stated.

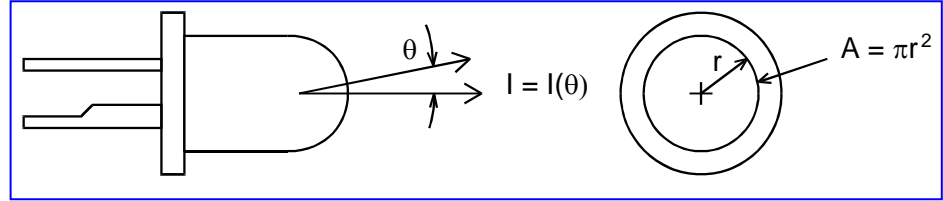
Perhaps after reading this, you have the opinion that we have simply made life difficult by attaching new terms to things already familiar. That is understandable; it may seem to be overkill. However, these terms have acquired an international acceptance and are precisely defined. The terms they replace have been too carelessly used and do not allow for the correct uncertainty treatment of all kinds of measurements, some of which can be exceptionally complicated, as with the measurement of fundamental constants. This terminology is being used throughout the world so that everybody will understand "precisely" what is being said about uncertainty.



B22 LUMINANCE OF AN LED

Problem: Given an ideal LED with radius $r = 3$ mm and rated at 300 mcd at 20 mA (15 cd/A), what is its luminance if the current is $J = 20$ mA?

An ideal LED, in this case, is one that appears to have a uniform luminance distribution when you look at it along its axis (perpendicular to its base), i.e., the area $A = \pi r^2 = 2.827 \times 10^{-5} \text{ m}^2$ appears to have a uniform



brightness. (Many LEDs appear relatively uniform to the eye.) The LED is rated (R) by a luminous intensity I produced by a certain current J : $R = I/J = 15$ cd/A. The luminance of a uniform disk is related to the luminous intensity for long distances (see § B3 for example) by $I = LA$. The luminance is then $L = I/A$, or in terms of the rating:

$$L = JR/A = 10\,610 \text{ cd/m}^2, \quad (1)$$

for a current of $J = 20$ mA.

B23 LUMINANCE OF LAMBERTIAN DISPLAY

Problem: Determine an expression for the luminance of a Lambertian display in terms of its luminous flux Φ and luminous efficacy η given a power input P .

The luminous efficacy is given by the ratio of the luminous flux Φ output to the electrical power P input.

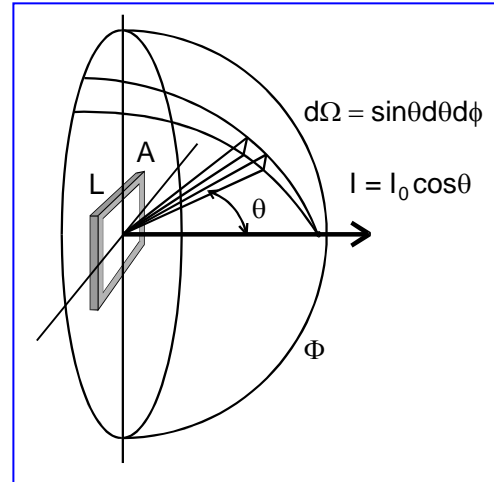
$$\eta = \Phi/P \quad [\text{lm/W}] \quad (1)$$

The luminous intensity of a Lambertian emitter is given by (see § B6)

$$I = I_0 \cos \theta, \quad (2)$$

where θ is the inclination angle and I_0 is the luminous intensity in the normal direction, $I_0 = LA$, and where L is constant, independent of direction. To get the luminous flux, we integrate the luminous intensity over the hemisphere; the element of flux in terms of an element of solid angle is $d\Phi = Id\Omega$, and using Eq. 2,

$$\Phi = \int_{\text{hemisphere}} Id\Omega = 2\pi LA \int_0^{\pi/2} \cos \theta \sin \theta d\theta = \pi LA \quad (3)$$



(where we used the substitution method with $u = \sin \theta$). Therefore, the luminance in terms of the flux is

$$L = \Phi/\pi A. \quad (4)$$

If we know the input power P and the luminous efficacy η , then from Eq. 1 we can write the luminance as

$$L = \eta P/\pi A. \quad (5)$$

For example, given a screen with area $A = 400 \text{ mm} \times 300 \text{ mm}$ ($H \times V$) = 0.12 m^2 , if the luminous efficacy is $\eta = 15 \text{ lm/W}$, and the power input is $P = 3 \text{ W}$, then the flux is $\Phi = 45 \text{ lm}$, and the luminance is $L = 119 \text{ cd/m}^2$.



B24 CONOSCOPIC LMDs

Conoscopic light-measuring devices (CLMDs) provide directionally resolved light measurements made with one laterally resolved exposure on an array detector. The basic principle of conoscopic equipment is the transformation of a directional distribution of elementary collimated beams of light into a lateral distribution (*directions image*). This transformation can be basically achieved with any positive lens. The *directions image* can be used for measuring any direction-dependent characteristics of the light originating from the field of measurement in the front focal plane. The directions image is usually captured by an additional lens system and projected on a detector array (e.g. CCD camera) for acquisition and evaluation.

Fisheye lens conoscopic LMDs can be used to make goniometric emission and transmission measurements on displays as well but using different imaging optics to those described herein. Using a fisheye lens with a very short minimum working distance this LMD images each angle of emission from the display from a unique location on the display.

A **conoscope** is an apparatus to carry out conoscopic observations and measurements, often realized by a polarization microscope with a Bertrand lens for observation of the *directions image* [1, 2]. The earliest references on the use of conoscopy (i.e., observation in convergent light with a polarization microscope with a Bertrand-lens) for evaluation of the optical properties of liquid crystalline mesophases (i.e., orientation of the optical axes) dates back to 1911 when it was used by Mauging to investigate the alignment of nematic and chiral-nematic phases [3]. **NOTE:** The use of the term “conoscope” in the context of display metrology is discouraged since this term is closely related to polarization microscopy, may be trademarked, and may refer to a commercial device.

Figure 1 illustrates the **basic concept of conoscopic LMDs** with a schematic raytracing: Transformation of a directional distribution of rays of incident light (red, green, blue) into a lateral distribution (*directions image*) appearing in the back focal plane (which is more or less curved). The incoming elementary collimated beams are converging in the back focal plane of the lens with the distance of their focal point from the optical axis, h , being a (monotonous) function of the angle of beam inclination (e.g., $h = f(\tan\theta)$). The image focal plane is also frequently referred as the “*Fourier plane*” in many optical sciences documents.

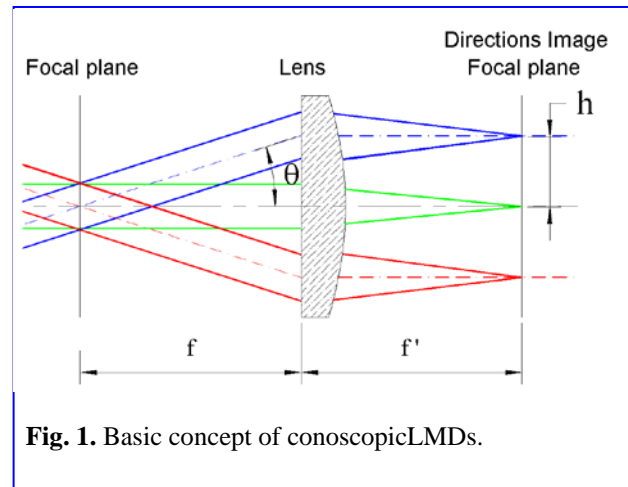


Fig. 1. Basic concept of conoscopic LMDs.

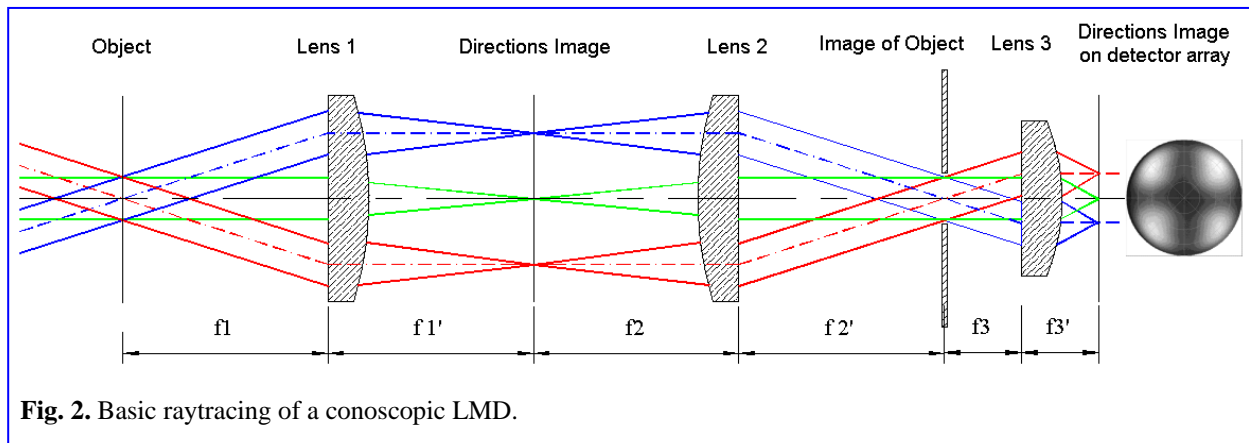


Fig. 2. Basic raytracing of a conoscopic LMD.

Figure 2 shows the basic ray tracing of a conoscopic LMD [9]. A conoscopic light measurement device usually comprises the following components (see Fig. 2):

1. a first lens that forms the image of the directional distribution of light (*directions image*),
2. a second lens used to create an image of the object on an adjustable aperture (iris diaphragm),
3. a third lens that forms a reduced directions image on an array of detectors (e.g., CCD or CMOS camera).

Lens2 and Lens3 together form a terrestrial (Keplerian) telescope. Depending on the realization of the optics, the first *directions image* may be an accessible real image, or it may be located within (or close to) a field lens. It is obvious that a large angle of inclination θ requires a transform lens with a high numerical aperture.



EFFECT OF OBJECT DISTANCE

If a device surface is placed in the front focal plane of the lens (if the entrance pupil of the system is located in the same plane as the object.), all the beams focused on the rear focal plane to form the *directions image* are originating from the same area (*field of measurement*) as illustrated in Fig. 1.

Figure 3 shows the raytracing with the measured device surface outside of the front focal plane—the entrance pupil of the system being outside of that plane. The rays of constant inclination θ originate from circular regions (annuli) about the optical axis. When the measured device surface is further away (and not located within the front focal plane), elementary parallel beams with different angles of inclination originate from annuli (circular rings) with different diameters. This is also the situation when fisheye lens LMDs are used to produce conoscopic images [7, 8, 10]. Fisheye lens LMDs have an image size that increases as the working distance increases. When using fisheye lens LMDs for inclination angles up to 80 degrees; working distances can be as small as 1mm and the total image size as small as 2cm. To avoid aliasing in the fisheye lens conoscopic image it is important to work at longer distances when the display pixels are larger.

When using a conoscopic LMD care must be taken when such a configuration is used to measure displays or display conditions:

1. Small displays or small areas on a display
2. Displays where lateral variations exists, like 3D displays of many kinds
3. Device characteristics at large angles where there is a high risk that the circular region of measurement exceed the size of the display.

THROUGH-THE-LENS ILLUMINATION OF REFLECTING OBJECTS

Non-emissive and non-backlit reflective samples can be illuminated through the front lens system (L1) either with a collimated beam or from within an extended solid angle (conical to hemispheric illumination), depending on the lateral distribution of the light source in the plane of the (primary or secondary) directions image.

Special care has to be taken during such measurements in order to characterize the unwanted reflections of the illuminating light in the conoscopic lens system for correction and compensation.

Figure 4 shows the illumination of the object of measurement through the imaging system. A point light source in the rear focal plane of the first (transform) lens with conical emission provides a collimated beam of illumination. If the rear focal plane of the transforms lens is completely filled with such light sources, the object of measurement is illuminated from all directions covered by the transform lens.

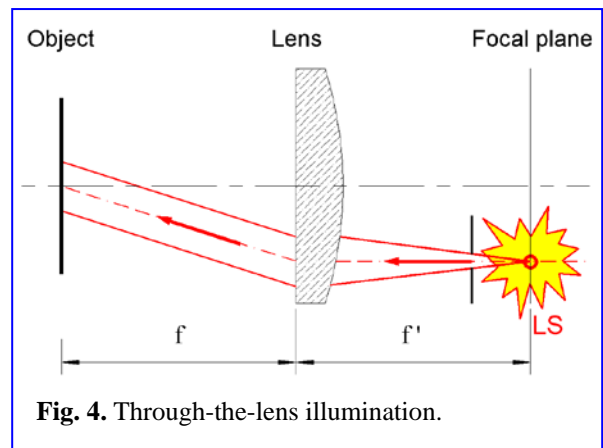


Fig. 4. Through-the-lens illumination.

FIELD OF MEASUREMENT VS. ANGLE OF INCLINATION

Depending on details of the realization of conoscopic LMDs the field of measurement ideally increases with $1/\cos\theta$ (as is the case with goniometric scanning of the viewing cone) ensuring a constant luminous flux or it remains constant with decreasing luminous flux.



DIAGNOSTICS FOR SYSTEM QUALITY

Quality assurance of a conoscopic LMD is similar to that of a conventional LMD. Indeed, such an instrument can be seen as many collimated-optics LMDs (as described in B19) working in parallel. Additions to A2, A3.3, A6 and A7 are discussed below

Lens flare diagnostic: As depicted in A2, lens flare and veiling glare can corrupt measurements through light that is reflected and diffused from optical elements inside the LMD (lenses, stops, baffles, etc.) or from surrounding equipment. It must be kept in mind that even if a FPD is very dark when viewed perpendicularly, light emitted at other angles can be significantly higher (many decades if we integrate the luminance over the actual solid angle). In such situations, parasitic light reflected from the environment needs to be taken into account. As compared with a conventional LMD, a conoscopic LMD sees only a limited part of the FPD due to its screen proximity, and also is protected from reflection to the environment. However, lens flare remains a concern.

Check for worst-case lens flare: The best way to check lens flare is to use specially designed "targets" in front of the equipment. The simplest one is composed of a reflective (aluminum or chromium) spot on a transparent support. The diameter D_1 of the spot is chosen large enough to include the measurement spot for all angles of inclination. If D_0 is the spot size, we need to have $D_1 > D_0 \cos \theta_{\max}$. D_0 is chosen significantly smaller than the usual spot (for example $D_0 = 150 \mu\text{m}$ and $D_1 = 1 \text{ mm}$). This target is then placed in front of a light source and the angular distribution of luminance on the opaque spot is measured. Integration over the whole solid angle can give the value of the "lens flare" flux on the sample and will represent the worst case lens flare effect. Both diffuse light (the output of an integrating sphere) and collimated light can be used for this measurement. In the second case, the influence of input light direction can be checked. Measurement can be normalized to light input by measuring the source without inserting the target in front of it. This test is very similar to what is done to check dark-room conditions.

Lens flare diagnostics with a collimated beam: The directional crosstalk of a conoscopic LMD can be checked with a collimated beam light source (unpolarized) that is mechanically adjusted to deliver light into the optical system from a range of directions of incidence. The lens flare of the equipment can be characterized in terms similar to the point spread function (PSF).

Compensation for veiling glare: The same procedure as described in A2.1.6 can be used for conoscopic LMDs as for conventional LMDs.

Linearity diagnostic: Section A3.3 fully applies. Linearity will be checked for all angles at the same time by collecting the data at the output of the integrating sphere.

Polarization diagnostic: Section A6 fully applies. Choose an incidence angle according to the polarization factor of the polarizer. To choose this angle, use a collimated light source with a polarizer in front. The incidence angle of the light beam can then be changed to check the equipment from perpendicular to maximum incidence angle.

Color measurement diagnostic: As explained in Section A7, the best color diagnostic is to check the measurement uncertainty for monochromatic light. This gives an absolute way of checking color-coordinate uncertainty. As shown on Fig. 4, place the conoscopic LMD in front of a diffuse monochromatic source of a desired wavelength, and check the system uncertainty (in x, y or u/v) for any desired viewing angle. It may be a good practice to make this measurement for each device or at least to have it provided by the manufacturer.

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B25 NEMA-DICOM GRAY SCALE

In display setup and metrology, it is sometimes useful to apply a table that relates differences in displayed luminance to a measure of the perceived contrast between these luminances. Such a table (included below with permission) has been developed by the National Electrical Manufacturers Association (NEMA) for application to Digital Imaging and Communications in Medicine (DICOM). The NEMA-DICOM grayscale table is a mapping from digital driving level to displayed luminance, designed so that equal steps in the digital driving level correspond to equal numbers of perceived just-noticeable differences (JNDs) in luminance. The scale is based on a model of human contrast sensitivity (P. G. J. Barten, Proc. SPIE 1666, 57-72 [1992] and Proc. SPIE 1913, 2-14 [1993]), which in turn was based on human contrast-detection experiments with spatial sine waves. In order for the gray scale to be independent of the displayed pattern, the scale was selected from the most sensitive Barten-model predictions over all patterns. In this way, it was ensured that in all cases the JND of luminance would be as small as possible, so that medical images with quantization errors less than 1 JND would be guaranteed not to show visible quantization artifacts. The scale is referenced as follows: “Digital Imaging and Communications in Medicine (DICOM) 4: Grayscale Standard Display Function. National Electrical Manufacturers Association (NEMA) Standard PS 3.14-1999.”

An equation summarizing the DICOM table (which should be implemented in double precision) is the following:

$$\log_{10}[L_j] = \frac{a + c \ln(j) + e[\ln(j)]^2 + g[\ln(j)]^3 + m[\ln(j)]^4}{1 + b \ln(j) + d[\ln(j)]^2 + f[\ln(j)]^3 + h[\ln(j)]^4 + k[\ln(j)]^5} \quad (1)$$

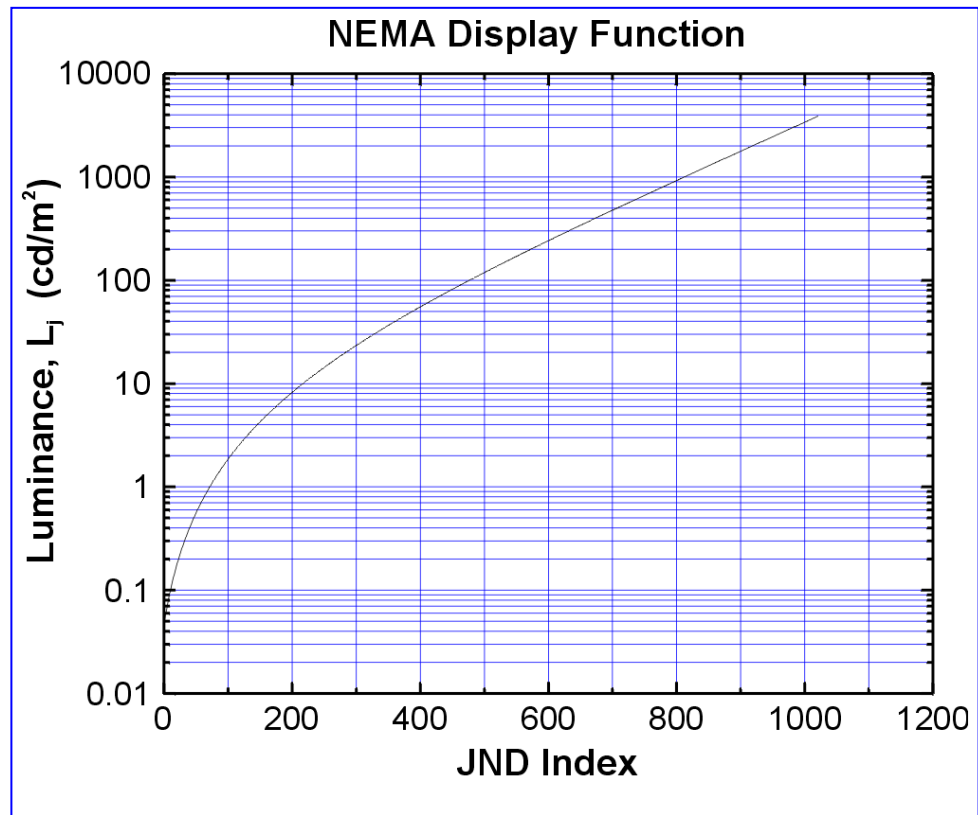
where $\ln(x)$ and $\log_{10}(x)$ are respectively the natural logarithm and the base-10 logarithm, j the JND index (1 of 1023) of the luminance levels L_j of the JNDs, and $a = -1.3011877$, $b = -2.5840191 \times 10^{-2}$, $c = 8.0242636 \times 10^{-2}$, $d = -1.0320229 \times 10^{-1}$, $e = 1.3646699 \times 10^{-1}$, $f = 2.8745620 \times 10^{-2}$, $g = -2.5468404 \times 10^{-2}$, $h = -3.1978977 \times 10^{-3}$, $k = 1.2992634 \times 10^{-4}$, $m = 1.3635334 \times 10^{-3}$. The inverse function is given by:

$$j(L) = A + B \log_{10}(L) + C[\log_{10}(L)]^2 + D[\log_{10}(L)]^3 + E[\log_{10}(L)]^4 + F[\log_{10}(L)]^5 + G[\log_{10}(L)]^6 + H[\log_{10}(L)]^7 + I[\log_{10}(L)]^8 \quad (2)$$

where $A = 71.498068$, $B = 94.593053$, $C = 41.912053$, $D = 9.8247004$, $E = 0.28175407$, $F = -1.1878455$, $G = -0.18014349$, $H = 0.14710899$, $I = -0.017046845$.

The NEMA-DICOM gray scale can be used in display setup to provide the best setting for the “brightness” and “contrast” controls. In a special gray scale test pattern, two specific step sizes (near white and near black) are adjusted until adjacent block luminances in this test pattern lie within a specified JND range of each other. Also, during display measurement, the gray scale can be used to assess the perceptual uniformity of the distribution of digital gray levels.

The figure shows the NEMA-DICOM function. The function relates just-noticeable-difference units (JNDs) of visibility to observed luminance. The table shows the JND grayscale as the JND index runs from 1 to 1023.





NEMA-DICOM JND GRAYSCALE

JND	L (cd/m ²)	89	1.4844	178	6.2521	267	17.0204	356	38.4340	445	78.6427	534	151.935	623	283.386	712	517.122	801	931.074	890	1663.51	979	2960.98
1	0.04999	90	1.5157	179	6.3334	268	17.1906	357	38.7617	446	79.2478	535	153.028	624	285.337	713	520.582	802	937.197	891	1674.35	980	2980.20
2	0.05469	91	1.5474	180	6.4153	269	17.3621	358	39.0916	447	79.8561	536	154.128	625	287.301	714	524.065	803	943.360	892	1685.25	981	2999.54
3	0.05938	92	1.5795	181	6.4981	270	17.5349	359	39.4239	448	80.4702	537	155.235	626	289.277	715	527.570	804	949.562	893	1696.23	982	3019.01
4	0.06435	93	1.6121	182	6.5815	271	17.7091	360	39.7585	449	81.0876	538	156.350	627	291.266	716	531.097	805	955.804	894	1707.28	983	3038.60
5	0.06957	94	1.6450	183	6.6658	272	17.8846	361	40.0955	450	81.7093	539	157.472	628	293.268	717	534.648	806	962.086	895	1718.40	984	3058.32
6	0.07502	95	1.6784	184	6.7508	273	18.0615	362	40.4349	451	82.3351	540	158.602	629	295.283	718	538.221	807	968.408	896	1729.59	985	3078.16
7	0.08070	96	1.7123	185	6.8365	274	18.2397	363	40.7767	452	82.9651	541	159.739	630	297.311	719	541.817	808	974.771	897	1740.85	986	3098.14
8	0.08661	97	1.7465	186	6.9231	275	18.4193	364	41.1209	453	83.5994	542	160.883	631	299.352	720	545.436	809	981.176	898	1752.19	987	3118.24
9	0.09274	98	1.7812	187	7.0104	276	18.6003	365	41.4675	454	84.2379	543	162.035	632	301.406	721	549.079	810	987.621	899	1763.59	988	3138.48
10	0.09909	99	1.8163	188	7.0985	277	18.7826	366	41.8166	455	84.8808	544	163.195	633	303.474	722	552.745	811	994.108	900	1775.07	989	3158.84
11	0.10566	100	1.8519	189	7.1874	278	18.9664	367	42.1682	456	85.5280	545	164.362	634	305.555	723	556.435	812	1000.64	901	1786.63	990	3179.34
12	0.11246	101	1.8879	190	7.2770	279	19.1515	368	42.5222	457	86.1796	546	165.536	635	307.649	724	560.148	813	1007.21	902	1798.26	991	3199.97
13	0.11948	102	1.9243	191	7.3675	280	19.3381	369	42.8787	458	86.8355	547	166.719	636	309.757	725	563.885	814	1013.82	903	1809.97	992	3220.73
14	0.12623	103	1.9612	192	7.4588	281	19.5261	370	43.2378	459	87.4959	548	167.909	637	311.879	726	567.647	815	1020.43	904	1821.75	993	3241.63
15	0.13421	104	1.9986	193	7.5509	282	19.7155	371	43.5993	460	88.1607	549	169.107	638	314.014	727	571.432	816	1027.17	905	1833.60	994	3262.66
16	0.14192	105	2.0364	194	7.6437	283	19.9064	372	43.9634	461	88.8300	550	170.313	639	316.164	728	575.242	817	1033.91	906	1845.54	995	3283.83
17	0.14986	106	2.0746	195	7.7375	284	20.0987	373	44.3301	462	89.5038	551	171.527	640	318.327	729	579.077	818	1040.70	907	1857.55	996	3305.14
18	0.15804	107	2.1133	196	7.8320	285	20.2925	374	44.6993	463	90.1822	552	172.749	641	320.504	730	582.936	819	1047.53	908	1869.63	997	3326.59
19	0.16645	108	2.1525	197	7.9274	286	20.4877	375	45.0711	464	90.8651	553	173.979	642	322.695	731	586.820	820	1054.40	909	1881.80	998	3348.17
20	0.17511	109	2.1922	198	8.0235	287	20.6845	376	45.4456	465	91.5525	554	175.216	643	324.901	732	590.729	821	1061.31	910	1894.04	999	3369.89
21	0.18401	110	2.2323	199	8.1206	288	20.8827	377	45.8226	466	92.2446	555	176.462	644	327.121	733	594.663	822	1068.27	911	1906.36	1000	3391.76
22	0.19315	111	2.2729	200	8.2185	289	21.0824	378	46.2023	467	92.9444	556	177.717	645	329.355	734	598.623	823	1075.28	912	1918.77	1001	3413.76
23	0.20254	112	2.3139	201	8.3172	290	21.2836	379	46.5847	468	93.6428	557	178.979	646	331.603	735	602.608	824	1082.33	913	1931.25	1002	3435.91
24	0.21218	113	2.3555	202	8.4168	291	21.4863	380	46.9697	469	94.3489	558	180.250	647	333.867	736	606.619	825	1089.43	914	1943.81	1003	3458.21
25	0.22207	114	2.3975	203	8.5172	292	21.6906	381	47.3575	470	95.0598	559	181.529	648	336.144	737	610.655	826	1096.57	915	1956.46	1004	3480.64
26	0.23221	115	2.4400	204	8.6185	293	21.8964	382	47.7479	471	95.7574	560	182.816	649	338.437	738	614.717	827	1103.75	916	1969.18	1005	3503.23
27	0.24261	116	2.4830	205	8.7207	294	22.1037	383	48.1410	472	96.4958	561	184.112	650	340.744	739	618.806	828	1110.99	917	1981.99	1006	3525.95
28	0.25327	117	2.5265	206	8.8238	295	22.3126	384	48.5370	473	97.2211	562	185.416	651	343.067	740	622.921	829	1118.27	918	1994.88	1007	3548.83
29	0.26418	118	2.5705	207	8.9277	296	22.5231	385	48.9356	474	97.9512	563	186.729	652	345.404	741	627.062	830	1125.60	919	2007.85	1008	3571.86
30	0.27536	119	2.6150	208	9.0326	297	22.7351	386	49.3371	475	98.6862	564	188.050	653	347.756	742	631.230	831	1132.97	920	2020.91	1009	3595.03
31	0.28681	120	2.6600	209	9.1383	298	22.9487	387	49.7413	476	99.4261	565	189.380	654	350.124	743	635.425	832	1140.39	921	2034.05	1010	3618.35
32	0.29852	121	2.7055	210	9.2449	299	23.1639	388	50.1484	477	100.171	566	190.719	655	352.507	744	639.647	833	1147.86	922	2047.27	1011	3641.83
33	0.31051	122	2.7515	211	9.3525	300	23.3808	389	50.5583	478	100.921	567	192.067	656	354.905	745	643.896	834	1155.38	923	2060.59	1012	3665.46
34	0.32276	123	2.7980	212	9.4609	301	23.5992	390	50.9710	479	101.676	568	193.423	657	357.319	746	648.172	835	1162.94	924	2073.98	1013	3689.24
35	0.33529	124	2.8450	213	9.5703	302	23.8193	391	51.3866	480	102.436	569	194.788	658	359.749	747	652.476	836	1170.56	925	2087.47	1014	3713.17
36	0.34809	125	2.8926	214	9.6806	303	24.0410	392	51.8051	481	103.201	570	196.162	659	362.194	748	656.807	837	1178.22	926	2101.04	1015	3737.27
37	0.36118	126	2.9406	215	9.7918	304	24.2643	393	52.2265	482	103.971	571	197.545	660	364.655	749	661.167	838	1185.93	927	2114.69	1016	3761.51
38	0.37454	127	2.9892	216	9.9040	305	24.4893	394	52.6509	483	104.746	572	198.938	661	367.132	750	665.554	839	1193.70	928	2128.44	1017	3785.92
39	0.38819	128	3.0384	217	10.0171	306	24.7160	395	53.0781	484	105.526	573	200.339	662	369.625	751	669.970	840	1201.51	929	2142.27	1018	3810.48
40	0.40213	129	3.0880	218	10.1312	307	24.9444	396	53.5084	485	106.312	574	201.749	663	372.134	752	674.414	841	1209.37	930	2156.20	1019	3835.20
41	0.41635	130	3.1382	219	10.2462	308	25.1744	397	53.9416	486	107.103	575	203.169	664	374.659	753	678.886	842	1217.28	931	2170.21	1020	3860.08
42	0.43086	131	3.1889	220	10.3621	309	25.4062	398	54.3778	487	107.899	576	204.598	665	377.200	754	683.388	843	1225.25	932	2184.32	1021	3885.13
43	0.44567	132	3.2402	221	10.4791	310	25.6396	399	54.8170	488	108.701	577	206.036	666	379.758	755	687.918	844	1233.26	933	2198.51	1022	3910.34
44	0.46077	133	3.2920	222	10.5970	311	25.8748	400	55.2593	489	109.507	578	207.484	667	382.333	756	692.478	845	1241.33	934	2212.80	1023	3935.71
45	0.47617	134	3.3444	223	10.7159	312	26.1117	401	55.7046	490	110.320	579	208.941	668	384.924	757	697.067	846	1249.45	935	2227.18		
46	0.49186	135	3.3973	224	10.8358	313	26.3504	402	56.1530	491	111.137	580	210.407	669	387.532	758	701.685	847	1257.62	936	2241.65		
47	0.50786	136	3.4508	225	10.9566	314	26.5908	403	56.6045	492	111.960	581	211.883	670	390.156	759	706.333	848	1265.84	937	2256.22		
48	0.52416	137	3.5049	226	11.0785	315	26.8330	404	57.0591	493	112.789	582	213.369	671	392.798	760	711.011	849	1274.12	938	2270.83		
49	0.54077	138	3.5595	227	11.2014	316	27.0770	405	57.5169	494	113.623	583	214.865	672	395.457	761	715.719	850	1282.45	939	2285.66		
50	0.55769	139	3.6146	228	11.3253	317	2																



B26 PERCEPTIVELY EQUAL GRAY-SHADE INTERVALS

An electronic display has a white luminance L_W and a black luminance L_K . We want to determine the luminances L_n for N perceptively equal gray shade intervals from black to white. Using the lightness metric of the CIE 1976 CIELUV and CIELAB color spaces the lightness L^* is

$$L^* = 116 \left(\frac{L}{L_W} \right)^{1/3} - 16, \quad (1)$$

$$\text{but } L^* = \left(\frac{29^3}{27} \right) \frac{L}{L_W}, \quad \text{for } \frac{L}{L_W} \leq \left(\frac{24}{116} \right)^3$$

There is a lightness associated with the white and black screen: $L^*_W = 100$, and L^*_K is given by Eq. (1) with $L = L_K$. The lightness levels for N perceptively equal intervals above black ($N+1$ levels in all) is

$$L^*_n = L^*_K + n \left(\frac{100 - L^*_K}{N} \right) \quad (2)$$

for $n = 0, 1, 2, \dots, N$ giving a total of $N+1$ levels including black ($n = 0$). For example, if $L_K = 0$ (a perfectly black screen ☺), then the lightnesses for $N = 6$ intervals would be $L^*_n = 0, 16.7, 33.3, 50, 66.7, 83.3, 100$, providing seven levels.

Equation (2) provides the lightness values producing perceptually equal gray-shade intervals from black to white. The corresponding luminances of the display would be the inversion of Eq. (1) using the L^*_n values:

$$L_n = \left(\frac{L^*_n + 16}{116} \right)^3 L_W, \quad (3)$$

$$\text{but } L_n = \frac{L^*_n L_W}{(29^3 / 27)} \quad \text{for } \frac{L_n}{L_W} \leq \left(\frac{24}{116} \right)^3$$

For our example with a perfectly black screen, if $L_K = 0$, and for $N = 6$ intervals, then the coefficients of L_W in the left side of Eq. (3) are: 0, 0.0223, 0.0769, 0.1842, 0.3619, 0.6279, 1; and if the luminance of white is $L_W = 100 \text{ cd/m}^2$, then the required luminances would be $L_n = 0, 2.2, 7.7, 18.4, 36.2, 62.8, 100 \text{ cd/m}^2$ — for this example only.

The L_n are the luminances that we would need to reproduce with the screen gray shades selected as nearly as possible to have our desired perceptibly equal luminance intervals from black to white. The luminance of a screen is determined by the driving level V —the gray level— and the electro-optical transfer function (sometimes called “gamma”) $L(V)$. In practice, once we have the desired luminance levels L_n , we might adjust the driving levels V until we get the desired luminance displayed on the screen as

closely as we can. To do this analytically, we would have to know the function form of $L(V)$ and be able to invert it $V(L)$ to obtain the desired driving levels $V_n = V(L_n)$. For discrete driving levels, the discrete level V_m that produces a luminance closest to L_n would be selected (m such that $|L_m(V_m) - L_n|$ is minimum).

Because very few displays have a zero black luminance, we cannot provide a general table for all displays illustrating the levels needed for different N values. The gray levels (command levels) employed to provide equal lightness steps (perceptively equal gray-shade intervals) will depend upon the measurement of the black luminance, the white luminance, and the above analysis that depends upon the electro-optical transfer function as well. We provide an example below, but it is *only* an example. Please do not use these values. Each display can be very different and needs to be measured separately to determine the correct gray levels (command levels) to use to provide perceptively equal gray-shade steps from black to white.

EXAMPLE ONLY: For example, let's assume that the display has a “gamma” of 2.5, whereby the electro-optical transfer function could be expressed as (assuming V for black is zero)

$$L = aV^\gamma + L_K, \quad (4a)$$

$$\text{where } a = \frac{L_W - L_K}{V_W^\gamma}. \quad (4b)$$

Inverted, we have

$$V = \left(\frac{L - L_K}{a} \right)^{1/\gamma}. \quad (5)$$

Assuming $L_W = 100 \text{ cd/m}^2$, $L_K = 0$, and that $V_W = 255$, we obtain $a = 9.6305 \times 10^{-5}$, and the gray levels (command levels) rounded to the nearest integer are: $V_n = 0, 56, 91, 139, 170, 212, 255$. Note, these numbers are for this simple and ideal example ONLY.



B27 BLUR, JUDDER, & SMOOTH-PURSUIT EYE TRACKING

We envision a vertical edge of an infinitely long block of one luminance L_j moving from left to right across a screen having a background luminance of L_i , where $i \neq j$. (See Fig. 1) We assume that for each refresh of the screen that this vertical edge moves (or jumps) a pixel increment of $\delta n \geq 1$; each region of width δn will be called a jump region. We want to calculate what the eye sees using the simplest model we can. In this analysis, we will assume pixels that are 100 % filled; that is, we will assume that the pixels have no structure and are uniformly filling the surface area allocated to them.

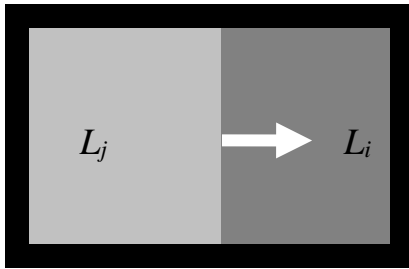


Fig. 1. Moving edge of one luminance over another.

A number of parameters need to be defined to deal with motion artifacts. Here is the list of variables used:

f = refresh rate (this is the frame rate for progressive-scan displays or the field rate for interlaced displays) in Hz:

$$f = 1/\delta t. \quad (1)$$

Note that f is the video refresh rate; that is, f is the rate at which information can be changed on the display surface. This refresh rate does not refer to any display framing rate that exceeds the rate at which information may be displayed. For example, a display may operate at 120 Hz in that it flips polarity at that rate, or it may operate at 180 Hz in a sequential mode, but in both cases, the video refresh rate is 60 Hz because the scene—the information—as viewed by the eye can only change at that slower rate.

δt = frame (or field) time interval in seconds (s):

$$\delta t = 1/f. \quad (2)$$

This is also known as the video refresh period or simply refresh period.

t = time in seconds from start of edge advancement:

$t = 0$ when the leading edge of the jump region is just to the left of the screen at the instant the leading edge is commanded to enter the screen area. For $t > 0$ the edge has jumped into the screen area at the left and the jump region begins to change (is activated) from the background. At $t = 0$ is the beginning of the first frame.

N_H = total integer number of pixels in the horizontal direction across the entire screen. N_H is an integer.

n = pixel index (count or address) in the horizontal direction from $n = 1$ at left to $n = N_H$ at the right-most pixel; n is an integer.

δn = pixel increment of advancement of the edge (jump in pixels) per screen refresh; δn is an integer.

N_R = total number of full jumps across the screen:

$$N_R = \text{int}(N_H/\delta n); \quad (3)$$

N_R is an integer.

k = integer number indexing the jump regions from left to right—a counter: $k = 1$ at the left side of the screen, and $k = N_R$ for the last complete jump region at the right of the screen. The index k is a spatial index that is used to locate each jump region across the screen.

t_k = time in seconds to the start of the activation of the k^{th} jump region

$$t_k = (k - 1)\delta t, \quad (4)$$

where $t_k = 0$ for $k = 1$, the first jump region.

u = edge average speed in px/s:

$$u = \delta n/\delta t. \quad (5)$$

If considered to be a velocity, it is directed toward the right.

x' = non-integer distance from the left edge of the screen measured in units of pixels (*not* distance).

The pixel n is related to x by

$$n = \text{int}(x') + 1, \quad (6)$$

where $0 \leq x' < N_H$ is a continuous unit of measure in pixels and n is an integer count of the number of pixels from the left of the screen. For example, if we are considering a point at the center of the 12th pixel, then $x' = 12.5$ px and $n = 12$. In terms of the actual distance x (in mm or m) from the left edge of the screen, $x' = x/p$, where p is the pixel pitch.

n_p = pixel location of the edge for ideal or perfect (infinitely fast) transitions:

$$n_p = n_p(t) = \delta n \text{ int}(t/\delta t). \quad (7)$$

This is equivalent to identifying the farthest pixel (to the right) that is commanded (turned on, activated) to the new level in the jump region.

SMOOTH-PURSUIT EYE TRACKING

We now assume that the eye smoothly follows the trailing edge of the moving edge—smooth-pursuit eye



tracking. This amounts to requiring the point of focus of the eye on the screen to move according to

$$x'_e = ut = \frac{\delta n}{\delta t} t, \quad (8)$$

which we will call the eye-tracking point—a continuous variable also in units of pixels that tells where the eye is looking as measured in units of pixels from the left of the screen. (The measure x'_e is exactly where on the screen the eye is looking in continuous units of pixels.) Relative to that eye-tracking point, we can think in terms of an on-screen relative retinal coordinate s that measures continuously in units of pixels from that eye-tracking point,

$$s = x' - x'_e, \quad (9)$$

which is simply the distance on the screen from the eye-tracking point measured in units of pixels. (To picture what s is, imagine a little x - y coordinate system that is centered at the point where the eye is looking, no matter where the eye looks—it moves around with the eye. The s coordinate is the horizontal position from the center of that little coordinate system in units of pixels along the x -axis or horizontal direction. This analysis is only concerned with the horizontal direction.) Combining these two equations, we can write a position on the screen in terms of the relative retinal coordinate and the time of observation since the start of the movement across the screen:

$$x' = s + ut. \quad (10)$$

And we can then write the pixel count n in terms of the relative retinal coordinate and time as

$$n = \text{int}(s + ut) + 1, \quad (11)$$

which assumes smooth-pursuit eye tracking of the trailing (left-most) edge of the jump region. See Fig. 2.

PERFECT TRANSITION VISUALIZATION

This section serves to illustrate how blur can arise because of smooth-pursuit eye tracking, although there may be no blur in the image on the screen. Let's confine our attention to the moving edge. At first we will consider that the transition between the two levels is perfect, that is, it is instantaneous, ideal. We will also consider the display to be on continuously; some call this a hold-type of display—where the luminance of a pixel (for this ideal case) will be essentially constant for the duration of the refresh period. Later we will incorporate temporal variations in the model.

Consider the smooth-pursuit eye-tracking model where the eye tracks the motion without any jerkiness (no saccades). If the eye smoothly tracks the average position of the trailing edge of our advancing region, the pixel position of that tracking is [Eq. (8)]

$$x'_e = ut = t \delta n / \delta t. \quad (12)$$

However, the edge is not moving smoothly, but moving along in jumps [according to Eq. (7)]:

$$n_p(t) = \delta n \text{int}(t / \delta t). \quad (13)$$

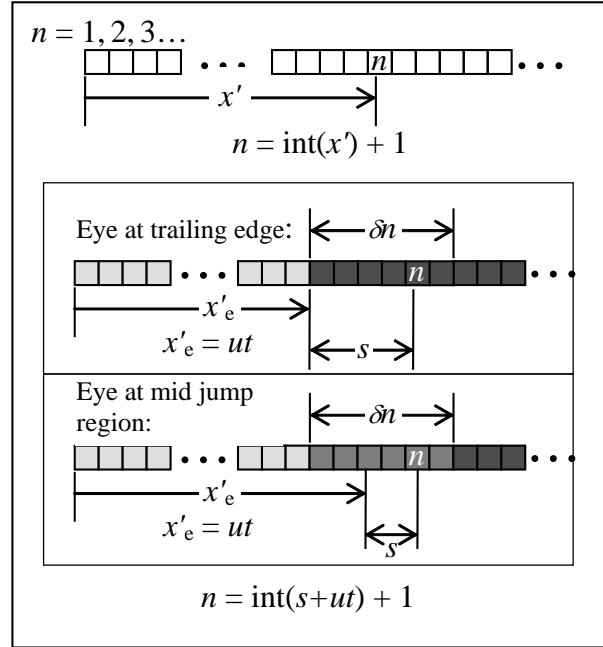


Fig. 2. Continuous variable x' in units of pixels and the on-screen relative retinal coordinate s also in units of pixels.

Because the eye is smoothly tracking the average position of the trailing edge, the position s_e of the edge as seen by the eye relative to its own moving coordinate system centered on the smooth-pursuit eye-tracking point is the difference between these quantities:

$$s_e(t) = n_p(t) - n_s(t), \quad (14)$$

which can be reduced to more basic quantities to give:

$$s_e(t) = \delta n [\text{int}(t / \delta t) - t / \delta t]. \quad (15)$$

This tracking gives rise to a sawtooth motion of the edge relative to the eye's gaze or tracking—see Fig. 3. If the

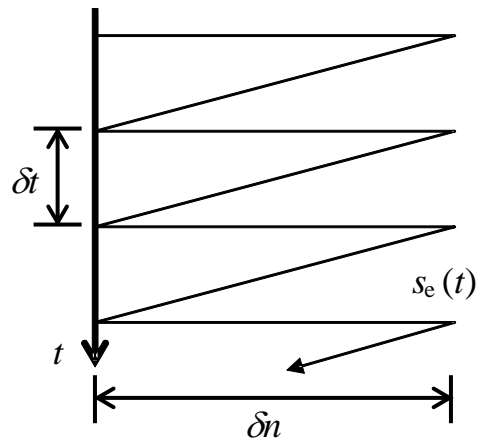


Fig. 3. Judder or blur arising from smooth-pursuit eye tracking of an ideal edge jumping across the screen in pixel increments of δn .



refresh rate is slow enough a jerkiness is observed that is called judder. If the refresh rate is fast enough the edge appears to be blurred even though the transition between luminance levels is instantaneous. Keep in mind that the model we are discussing in this section only is for a hold type of a display where the pixels are illuminated throughout the refresh time and the transitions are perfect (instantaneous). The analysis that follows is general and does not require us to consider perfect transitions or even hold-type of displays. The following analysis will apply to impulsive displays (such as CRTs) as well as hold-type displays (such as LCDs).

SMOOTH-PURSUIT EYE-TRACKING ASSUMING BLUR

We will now consider the case where we have a sufficiently fast refresh that we don't see judder, but we only see blur. We will consider a horizontal row of pixels or a narrow horizontal band of pixels and assume that all the pixels in any column n activate and perform the same way. Thus, we can write the luminance of that band (or row) as a function of pixel n and time t :

$$L_{ij} = L_{ij}(n, t). \quad (16)$$

Let's look at the edge near the center of the screen where we define

$$c = \text{int}\left(\frac{N_H}{2\delta n}\right) \quad (17)$$

to be the number of the beginning of a jump region just to the left of center or at the center. Because we are assuming blur, we can simply integrate the luminance L_{ij} for the edge transition near the center over a single refresh time period. However, because the eye-tracking point is not stationary, but moves across the jump region; we need to express n in terms of the eye-tracking coordinates in order to obtain what the eye sees $K_{ij}(s)$ in terms of its own relative-retinal coordinates s . From Eq. (11) we have n in terms of s to obtain:

$$K_{ij}(s) = \frac{1}{\delta t} \int_{c\delta t}^{(c+1)\delta t} L_{ij}([\text{int}(s + ut) + 1], t) dt. \quad (18)$$

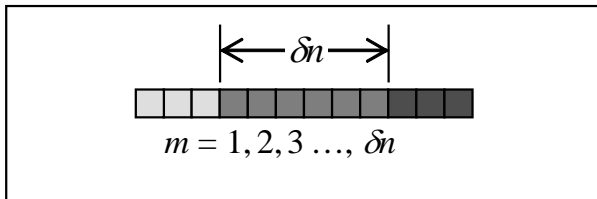


Fig. 4. Pixels within any jump region are labeled with the index m .

This provides us with the luminance as a function of continuous pixel position from the smooth-pursuit-eye-tracking point moving along with the edge motion at speed u . A pursuit camera that is moving with speed u and integrates for exactly one refresh period will obtain $K_{ij}(s)$

directly (scaled appropriately in terms of s versus the camera pixels). Capturing an integer number of jump regions may be useful for noise reduction. If N jump regions are used, then the integral in Eq. (18) would be divided by N and the upper limit of integration would be $(c + 1 + N)\delta t$.

MOVING EDGE SCREEN LUMINANCE

We now want to determine an expression for screen luminance $L_{ij}(n, t)$ for an edge that moves in jumps based upon how the pixels change from one luminance L_i to a new luminance L_j . Once an expression for $L_{ij}(n, t)$ is obtained, we may get some clues as to how many different ways it can be measured.

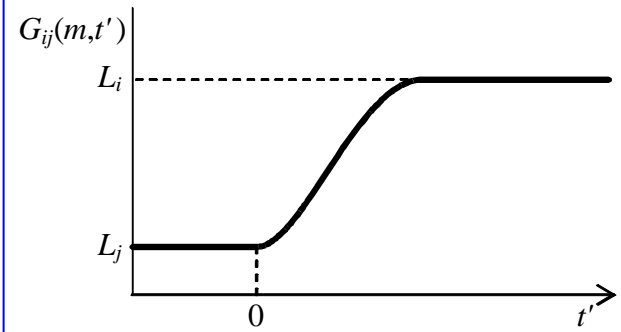


Fig. 5. Transition luminance response for each pixel m within a jump region.

Within any jump region, we label the pixels with an index $m = 1, 2, 3, \dots, \delta n$. See Fig. 4. Consider any jump region. For each pixel n in the row of that jump region, suppose we know how the luminance changes for any transition $i \neq j$ as the edge moves by that jump region; call this the transition luminance response $G_{ij}(m, t')$ —see Fig. 5. Here, t' is the time as measured within any jump region. For this transition luminance response, $G_{ij}(m, t')$, suppose that the zero time, $t' = 0$, marks the beginning of the transition and is the same for all pixels within that jump region. What we now want to do is to write an expression for $L_{ij}(n, t)$ based upon this understanding of how the jump region changes.

We can write the luminance of the screen $L_{ij}(n, t)$ in terms of $G_{ij}(m, t')$ where we somehow confine the quantities m and t' to correctly describe the moving edge. To do this, we will introduce the sequencing factor

$$\text{int}\left(\frac{n-1}{\delta n}\right), \quad (19)$$

which provides an ordering of the jump regions. In fact, the jump region index k can be defined by

$$k = \text{int}\left(\frac{n-1}{\delta n}\right) + 1. \quad (20)$$

The time of activation of the k^{th} jump region [Eq. (4)] now becomes



$$t_k = \delta t \operatorname{int}\left(\frac{n-1}{\delta n}\right). \quad (21)$$

Table 1 illustrates how this sequencing factor functions as a way to order the jump regions. Essentially it tells us what jump region we are observing given any value of n . This sequencing factor will permit our regulation of the activities within the jump regions by using only the pixel position n , and it will permit us to write a comparatively simple expression for the screen luminance $L_{ij}(n, t)$.

We can now express the screen luminance $L_{ij}(n, t)$ for the entire screen in terms of the transition luminance response $G_{ij}(m, t')$ of a single jump region by carefully defining m and t' so that the screen is activated via a sequence of jump regions having the same response but at different times and places:

$$L_{ij}(n, t) = G_{ij}(m, t'), \quad (22)$$

where

$$m = n - \delta n \operatorname{int}\left(\frac{n-1}{\delta n}\right), \quad (23)$$

and

$$t' = t - t_k = t - \delta t \operatorname{int}\left(\frac{n-1}{\delta n}\right). \quad (24)$$

You will note the appearance of t_k as the expression after the minus sign. Thus t' remains less than zero until $t > t_k$. This is precisely what we want for the time-based motion of the edge moving in jumps. The jump regions activate sequentially. We can put this all together, but the expression is cumbersome and not particularly illuminating:

$$L_{ij}(n, t) = G_{ij}\left[\left[n - \delta n \operatorname{int}\left(\frac{n-1}{\delta n}\right)\right], \left[t - \delta t \operatorname{int}\left(\frac{n-1}{\delta n}\right)\right]\right]. \quad (25)$$

The term m recycles through each jump region; so, it keeps track of where we are within any jump region no matter at which pixel n we are looking. The term t' activates the jump region at the appropriate time so that the edge moves across the screen in increments of δn for each refresh period δt . For times $t' \leq 0$ then $G_{ij}(m, t') = L_i$; and for long times, $G_{ij}(m, \infty) = L_j$.

In actuality, we rarely measure the luminance values $G_{ij}(m, t')$ directly. We usually measure a voltage, a current, or obtain some detector pixel count (or level) in some sort of a digitized detector such as a CCD camera. Let g be what we actually measure, and assume it comes from a linear detector with a possible offset of g_0 — see Fig. 6. We can associate g_w with the white luminance L_w , g_K with black L_K , g_i with L_i , g_j with L_j , etc. The relationship between G and g is:

$$G_{ij}(m, t') = L_w \frac{g_{ij}(m, t' + t_g) - g_0}{g_w - g_0}. \quad (26)$$

Here the time scale of the recorded data g is shifted so that at $t' = 0$ the transition for $G_{ij}(m, t')$ begins. (We are also assuming that for no luminance, $L = 0$, then it must be that $G = 0$.)

What this analysis demonstrates is that if we can carefully measure the detailed time dependence of a jump region, then we can write the entire screen luminance $L_{ij}(n, t)$ as a function of time. Once we have $L_{ij}(n, t)$, then we can use Eq. (18) to determine what the eye sees assuming smooth-pursuit eye tracking, $K_{ij}(s)$.

Table 1. Jump region ordering.

k	Range of n	$\operatorname{int}\left(\frac{n-1}{\delta n}\right)$
1	$1 \leq n \leq \delta n$	0
2	$\delta n + 1 \leq n \leq 2\delta n$	1
3	$2\delta n + 1 \leq n \leq 3\delta n$	2
$N_R = \operatorname{int}(N_H/\delta n)$	$(N_R - 1)\delta n + 1 \leq n \leq N_R\delta n$	$(N_R - 1)$

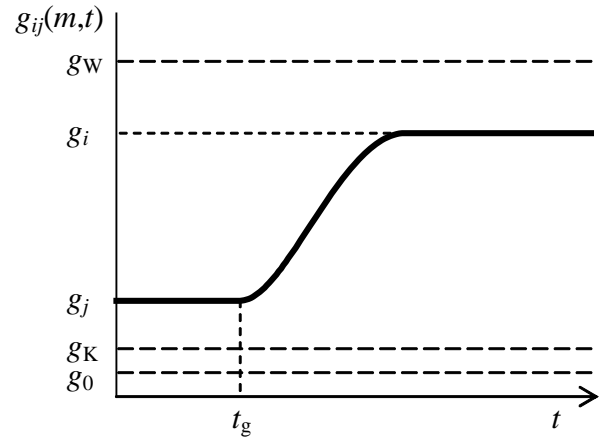
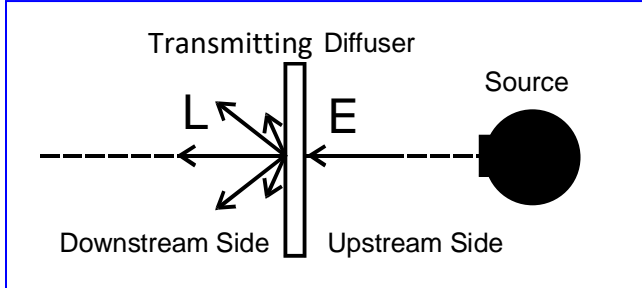


Fig. 6. Data obtained from linear detector to provide an indication of the luminance of the m^{th} pixel in a jump region as a function of time.



B28 TRANSMITTING DIFFUSER— L VS. E

Problem: Given an illuminance $E = 1000$ lx falling upon the back side of a transmitting diffuser with a diffuse transmittance of $\tau = 0.3$, what is the illuminance L on the other side?



The transmittance is defined as the ratio of the flux transmitted to the flux incident. We will assume the diffuser is a perfect (Lambertian) diffuser for the purposes of this calculation. Let a flux Φ be incident on an area A of the back of the diffuser. The illuminance is

$$E = \Phi/A . \quad (1)$$

The luminous exitance M out the other side is

$$M = \tau E , \quad (2)$$

because the transmitted flux is $\tau \Phi$. For such a Lambertian emitter, the luminance L is given by

$$L = M/\pi \quad (3)$$

(see § B15). In terms of the incident illuminance E this becomes

$$L = \tau E/\pi . \quad (4)$$

For an illuminance of $E = 1000$ lx and flux transmittance of $\tau = 0.3$, the luminance will be $L = 95$ cd/m². Provided the transmitting diffuser is really Lambertian, by measuring the illuminance on one side (the upstream side) and luminance on the other side (the downstream side) we can estimate the transmittance from

$$\tau = \pi L / E , \quad (5)$$

which only applies for a perfect (Lambertian) diffuser.

In the event that that the leap to Eq. (3) was a bit large, let's take a little more time with it: For any surface of area A and luminance L , the luminous intensity I is given by

$$I = LA \cos \theta , \quad (6)$$

where θ is the angle from the normal of the surface. For a Lambertian surface the luminance L is constant (independent of θ):

$$L = L(\theta) = \text{constant.} \quad [\text{Lambertian}] \quad (7)$$

The transmitted flux MA is the hemispherical integration of $I(\theta)$ in Eq. (6):

$$MA = LA \int_0^{2\pi} d\phi \int_0^{\pi/2} \cos \theta \sin \theta d\theta = \pi LA . \quad (8)$$

This reduces to Eq. (3).

Practical Considerations: In actuality, many such transmissive diffusers are supplied with glossy surfaces. Sanding the glossy diffusing surfaces with sandpaper (about 240 grit or so) may make for a better diffuser (more Lambertian) but with possibly more transmission loss and more vulnerability to dirt. The diffusing surface for opal glass is on one side of the glass plate. For milky acrylic plastic as used for advertising signage the diffusion occurs throughout the thickness of the medium. The diffusion of the plastic material may also be enhanced by sanding the surfaces. Sometimes such milky plastic will produce a dim but distinct image of the source. By sanding the plastic surfaces, the distinct image can be eliminated thereby improving the diffusion properties of the plastic (generally, any visibility of a distinct image is not a problem with opal glass). Just sanding the surfaces of regular clear glass or clear plastic will not produce a very Lambertian surface. The use of such diffusers as opal glass and white plastic will also result in a yellowing of the transmitted light (the sky is blue and sunsets are red, do you see the relationship?).

Rough Measurements: For an opal glass sample (not sanded) we measured an incident illuminance of 910 lx and obtained a luminance of the other side of only 130 cd/m², which gives a value of $\tau = 0.45$ from Eq. (5). Using a milky-white acrylic plastic sheet sanded on both sides, we obtained a luminance of 110 cd/m² with 990 lx illuminance on the other side, which gives a value of $\tau = 0.35$ from Eq. (5). Note, again, that Eq. (5) assumes a Lambertian diffuser, which probably is not the case.



B29 GAMUT AREA AND OVERLAP METRICS

ALIAS: Figures of Merit for Emissive-Display Color Gamuts

This section describes a metric for the color gamut of a three-primary emissive display system. A display's color gamut is the set of points in a color space that are producible by the display. One possible gamut metric would be a volume in a CIE uniform color space, in which equal distances correspond approximately to equal color differences. However, such a volume would depend on the gains of the primaries, and on the white of the display. These quantities are subject to change during display calibration, and thus cannot usefully characterize a display. Another possible metric might involve saturation of the primaries, but again this metric is not useful because it depends on the monitor white.

However, the chromaticities of most emissive-display primaries are stable enough to use in a metric, particularly if the chromaticity coordinate system is approximately uniform perceptually. One uniform-color space, CIELUV,¹ has embedded in it a chromaticity space (u', v') that is used widely in the display industry for such metrics as screen uniformity.^{2, 3} Also, some ANSI standards specify measurement of chromaticities in (u', v') coordinates.⁴ Finally, the area in a uniform chromaticity space has long been regarded as a reasonable figure-of-merit for color gamut.⁵ Therefore, the metric proposed here is the area of the triangle subtended by the primaries (R,G,B) in the chromaticity space whose coordinates are (u', v').

Pictorially, the area metric is a percentage of the area subtended by the entire spectrum locus in (u', v') space, which is the maximum gamut of any color system, no matter how many primaries are used in the system. [Note: The area of the spectrum locus is computed as the area of the polygon whose vertices are the chromaticities of spectral lights from 380 nm to 700 nm in increments of 1 nm. The computed value of this area is 0.1952.]

AREA-GAMUT METRIC

If the measurement device measures CIE (x, y) values but not (u', v') values, then:

- Measure CIE (x, y) values for each primary at full-on (with the other primaries turned off). Denote the (x, y) values as (x_R, y_R) for the red primary, (x_G, y_G) for the green primary, and (x_B, y_B) for the blue primary.
- Transform each of the (x, y) pairs defined above to the CIE 1976 (u', v') coordinate system, using the following equations:

$$u' = 4x / (3 + 12y - 2x)$$

$$v' = 9y / (3 + 12y - 2x)$$

- Compute the area of the rgb triangle in (u', v') space, divide by 0.1952, and multiply by 100 %, to obtain

$$A = 256.1 |(u'_R - u'_B)(v'_G - v'_B) - (u'_G - u'_B)(v'_R - v'_B)|.$$

Alternatively, if the coordinates (u', v') are directly available from the measurement instrument, one can skip steps (a) and (b) above and proceed directly to (c).

EXAMPLE CALCULATION

The following coordinates were measured on a particular projector:

$$\text{Red: } u'_R = 0.443, v'_R = 0.529$$

$$\text{Green: } u'_G = 0.124, v'_G = 0.567$$

$$\text{Blue: } u'_B = 0.186, v'_B = 0.120$$

From these coordinates, the area-gamut metric is $A = 36$ as computed from the equation in Step (c) above. That means the display has access to 36 percent of the area inside the spectrum locus.

METRIC OF OVERLAP GAMUT

In evaluating a color gamut, size is not everything. One also wants to know the fraction of overlap of the gamut with that of a reference display (such as NTSC, ITU Rec 709, or other).

In $u'v'$ space, let A be a test display's area-gamut metric (percentage of the spectrum-locus area occupied by a display's gamut polygon---allowing for displays with more than 3 primaries). Similarly define A_0 for the reference display. For a convex polygon, the area can be evaluated as follows: choose a center point w (perhaps a white) inside the polygon, and label points 1, 2, 3, etc. counterclockwise about w ; then compute the area of each triangle as done for the primary triangle earlier in this section. To arrive at an area metric, normalize the area with respect to that of the spectrum locus as described earlier.

Let g be the fraction of the reference-gamut area that is also part of the test-display's gamut polygon. (This represents "overlap gamut.") The overlap polygon will be convex and amenable to the same technique as above. Of course, the center point w may have to be freshly selected so as to lie inside the overlap polygon.



To compute g , it is probably easiest to count (u', v') pixels (little squares of $\Delta u \times \Delta v$, recommended to be at least 0.001 in size) in the overlap area of triangles P and Q (i.e., test if a pixel is in both triangles P and Q, and increment the area counter if the pixel passes the test). One can also analytically find the areas of constituent polygons, but that approach is probably not worth the effort because too many special cases are possible.

A POSSIBLE SINGLE-NUMBER SUMMARY METRIC

For a single-number summary of gamut area and overlap area, one could choose a metric H that is zero if the test and reference gamuts do not intersect (i.e., if $g = 0$), is the relative area A/A_0 (not to exceed 1) if the test gamut lies entirely within the reference gamut and gives extra credit for parts of the test gamut that lie outside the reference gamut. One choice is

$$H = g A/A_0.$$

In terms of areas (rather than relative areas), the rule is $H = a A'/A_0^2$, where a is the overlap area of reference and test gamuts, A' is the test-gamut area, and A_0 is the area of the reference gamut. Notice that the total area inside the spectrum locus canceled here.

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B30 EYE-HEALTH ALERT

Diversity and ubiquity of fluorescent-backlit LCD's raise questions of eye safety. Such questions are made more urgent by users' habit of staring at LCD computer screens for upward of eight hours a day. The following kinds of eye damage are of concern: Eye damage including cataracts and snow blindness, incurred by ultraviolet (UV) radiation (with greatest efficiency near 270 nm [1]). Retinal photochemical damage including macular degeneration due to strong blue light near 430 nm. [2]

Many filters and other plastic fronting materials used in LCDs will transmit so little UV as to make the first of these hazards negligible. However, some light-transmitting materials also transmit in the UV [3], and fluorescent lights are also diverse enough to include UV generation. Compounding this problem is the rarity of UV-spectrum-measuring devices, that rarity being partly due to the fact that most spectrometers have optics that are made of glass and don't transmit UV efficiently enough to measure radiation below about 380 nm. As a result of measurement difficulties, each new LCD model is a new unknown in terms of UV emission.

Eye hazards in the presence of blue light are also well documented. A photochemical retinal hazard has been observed with peak sensitivity near 430 nm [4], and macular degeneration tends to increase when strong blue lights are used for diurnal-rhythm therapy [2]. We should be ready for quantitative standards to emerge. However, common sense suggests that prolonged use of very bright displays with very blue-white points may not be well tolerated by eyes, especially in older and susceptible people.

This note is intended as an alert so that future editions of this and other display metrology standards can attend to the increasingly urgent task of UV measurement. The question of blue-light mitigation is not a matter for metrology: We can measure what any LCD delivers. However, a general caveat about displays seemed warranted in this context.

References

- [1] International Non-Ionizing Radiation Committee of the International Radiation Protection Association, Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation), *Health Physics* **87** (2), 177-186 (2004).
- [2] <http://www.sunnexbiotech.com/therapist/main.htm> and see primary research references therein.
- [3] This link to an old (1981) article shows a tinted plastic that transmits 80 percent of radiation at 350 nm: <http://archophth.highwire.org/cgi/reprint/99/2/293.pdf>
- [4] American Conference of Governmental Industrial Hygienists (ACGIH) 2020 TLV's, *Threshold Limit Values and Biological Exposure Indices for 2010*, Cincinnati: ACGIH.



B31 SPECULAR REFLECTANCE AND LUMINANCE FACTOR

Problem: Given a uniform source with area A_s and luminance L_s suppose we use it in a specular configuration and determine the specular reflectance ζ of a display. What relationship, if any, is the specular reflectance to the luminance factor β ?

The luminance we measure in the specular direction is

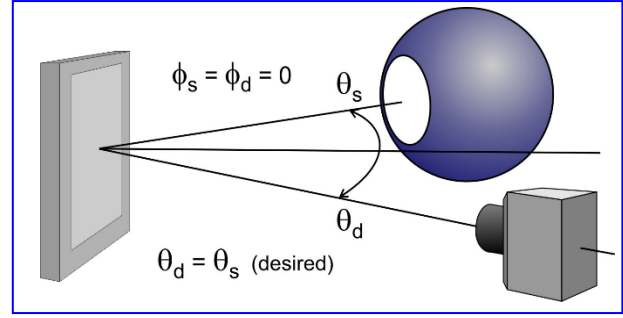
$$L = \zeta L_s. \quad (1)$$

Assuming large distances and small areas (which is not really correct, but let's see where this goes) from such a source is (see B14 Illuminance from Luminance)

$$E = \frac{L_s A_s \cos \theta_s}{c_s^2}. \quad (2)$$

If we determined the luminance factor instead of the specular reflectance,

$$\beta = \frac{\pi L}{E}, \quad (3)$$



then we can express this in terms of the specular reflectance and the expression for the illuminance:

$$\beta = \frac{\pi c_s^2}{A_s \cos \theta_s} \zeta \quad (4)$$

The relationship is geometrical. Makes sense. ...Well, that didn't go very far.

B32 NEMA-DICOM & EPD GRAY SCALE FUNCTIONS

The luminance response of a display determines the visibility of the gray shades. For example, luminance response curves have been standardized for the medical community by the National Electrical Manufacturers Association (NEMA) for application to Digital Imaging and Communications in Medicine (DICOM) ^[1], and for the geospatial intelligence community by the National Geospatial-Intelligence Agency (NGA) Image Quality and Utility (NIQU) Program ^[2]. The mathematical relationship between input digital driving level to output displayed luminance is specified for each of these standards. In practice, the input drive levels to the display are mapped through a look-up-table (LUT) to achieve the desired output luminance response.

The NEMA-DICOM grayscale function (GSDF: see Tutorial Appendix § B25 NEMA-DICOM Gray Scale for details and a table of numbers) assures each successive increase in input drive gray level produces an equal increase in perceived luminance measured in units of Just Noticeable Difference (JND) ^[3,4]. JNDs are based on human contrast sensitivity models. The DICOM grayscale function is defined as:

$$\log_{10}[L_j] = \frac{a + c \ln(j) + e[\ln(j)]^2 + g[\ln(j)]^3 + m[\ln(j)]^4}{1 + b \ln(j) + d[\ln(j)]^2 + f[\ln(j)]^3 + h[\ln(j)]^4 + k[\ln(j)]^5} \quad (1)$$

where $\ln(x)$ and $\log_{10}(x)$ are respectively the natural logarithm and the base-10 logarithm, j the JND index (1 of 1023) of the luminance levels L_j of the JNDs, and $a = -1.3011877$, $b = -2.5840191 \times 10^{-2}$, $c = 8.0242636 \times 10^{-2}$, $d = -1.0320229 \times 10^{-1}$, $e = 1.3646699 \times 10^{-1}$, $f = 2.8745620 \times 10^{-2}$, $g = -2.5468404 \times 10^{-2}$, $h = -3.1978977 \times 10^{-3}$, $k = 1.2992634 \times 10^{-4}$, $m = 1.3635334 \times 10^{-3}$.

The inverse DICOM function is given by:

$$j(L) = A + B \log_{10}(L) + C[\log_{10}(L)]^2 + D[\log_{10}(L)]^3 + E[\log_{10}(L)]^4 + F[\log_{10}(L)]^5 + G[\log_{10}(L)]^6 + H[\log_{10}(L)]^7 + I[\log_{10}(L)]^8 \quad (2)$$

where $A = 71.498068$, $B = 94.593053$, $C = 41.912053$, $D = 9.8247004$, $E = 0.28175407$, $F = -1.1878455$, $G = -0.18014349$, $H = 0.14710899$, $I = -0.017046845$. Note: because the sensitivity of the eye to gray levels is different at lower versus high levels, the display luminance has to be maintained constant after the calibration to a GSDF curve was done.



The Equal Probability of Detection (EPD, symbol D_{EP} , see appendix A12.6) grayscale function differs from the DICOM function in that luminance steps among the darker gray levels are boosted slightly to enhance visual detection of dimmer low-contrast objects of interest residing among brighter surrounding areas in the image. The EPD luminance response function in cd/m^2 is given by:

$$D_{EP} = (0.2 + 8.1206638x - 12.453941x^2 + 96.293375x^3 - 121.85936x^4 + 99.699238x^5) / 0.2919$$

where x is the input command value normalized from 0 to 1 and produces an output luminance ranging from black $L_{\min} = 0.685 \text{ cd/m}^2$ to white $L_{\max} = 239.8 \text{ cd/m}^2$. The polynomial is divided by 0.2919 to convert from fL to cd/m^2 . While the given EPD polynomial has not been formally validated outside this range, it is typically normalized, then offset and scaled to fit other black and white luminance levels. Note: The EPD grayscale function is limited to a luminance range, and therefore after calibration the luminance levels have to be maintained. A spreadsheet that carries out the above calculations is available at <https://doi.org/10.55410/cbol4505>.

- [1] Digital Imaging and Communications in Medicine (DICOM) 4: Grayscale Standard Display Function. National Electrical Manufacturers Association (NEMA) Standard PS 3.14-1999.
- [2] Softcopy Exploitation Display Hardware Performance Standard Version 3.1, 05 March 2010, National-Geospatial Intelligence Agency (NGA) Image Quality and Utility (IQ&U) Program available at: <https://www.gwg.nga.mil/protected/ntb/index.html>. You may submit a request for access at: <http://www.gwg.nga.mil/access.php>.
- [3] P. G. J. Barten, Proc. SPIE 1666, 57-72 [1992]
- [4] Proc. SPIE 1913, 2-14 [1993]

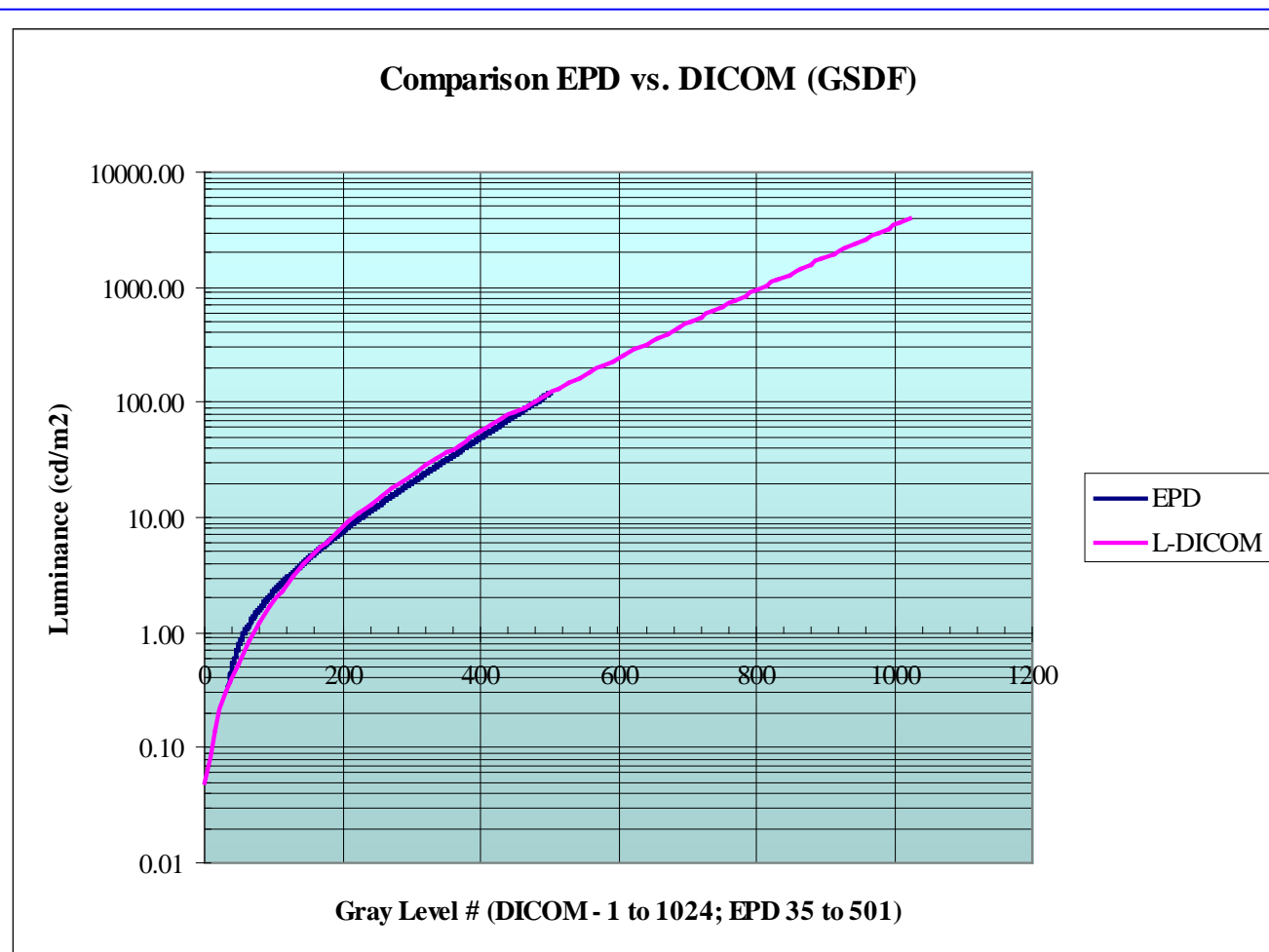


Fig. 1. Comparison of EPD and DICOM (GSDF) curves where DICOM (GSDF) is between gray levels 1 and 1024 while EPD is between 35 and 501 to match the luminance levels.



B33 HDR ECOSYSTEM FROM THE METROLOGY VIEWPOINT

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B33.1 Overview

This tutorial describes the fundamental properties of current HDR imaging pipelines including signal properties, tone and gamut mapping, and display hardware behavior. The challenges to reproduce HDR signals accurately are significantly higher than those for reproducing SDR signals. Depending on the properties of an HDR signal, the corresponding metadata information, and the display status conditions, measurement results may vary substantially. It is therefore imperative to be aware, to control, and to record and report metrological results. Many areas still require considerable amounts of research, both in the larger HDR ecosystem as well as in the scope of metrology, in order to being able to measure with the level of precision intended by the ICDM.

B33.2 Introduction

Compared to the early years of digital displays, modern electronic displays have significantly increased in capability in order to further the image fidelity and accuracy available to viewers, both in the consumer and professional spaces. The Human



Visual System (HVS) can fundamentally cover a large dynamic range⁵, spanning over a dozen orders of magnitude. To make more realistic experiences possible, significant improvements had to be introduced to all aspects of the imaging ecosystem, including image capture, processing, storage, transport, manipulation, and display. The term High Dynamic Range (HDR) is used to refer to the expanded dynamic range of light intensities for each of these elements. The main elements of the HDR ecosystem can also be interpreted in the context of an imaging pipeline, where one element interacts with the next. As an overview, Fig. 1 shows modernized elements of the imaging pipeline and absolute light levels at each stage. Some of the most fundamental improvements have been in the capture or image generation (b-c), processing and distribution (d), and display (e-f) stages. Today, HDR technology is well established in the consumer TV segment and it is also successively finding its way into computer, mobile, and information displays as well as projection systems.

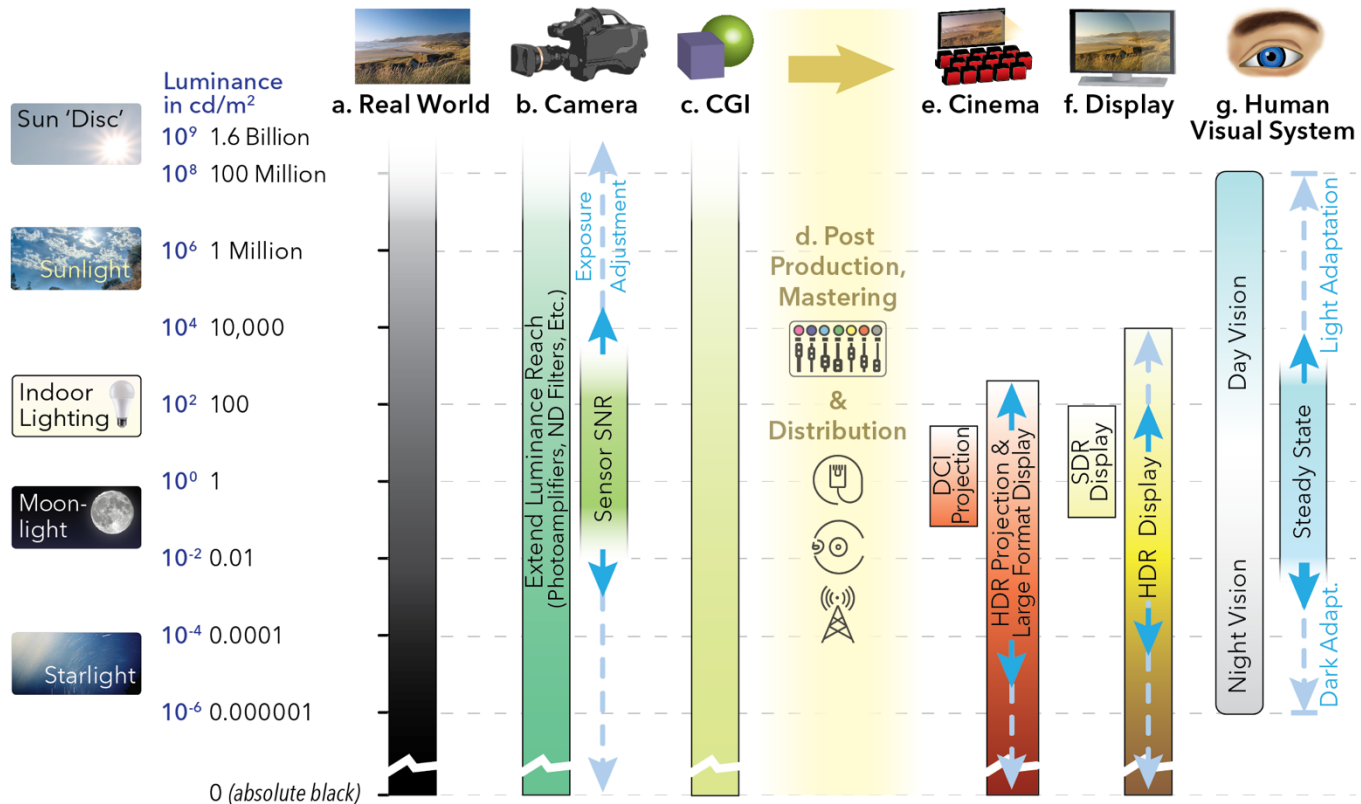


Fig. 1. Light levels and dynamic ranges of real world (a) and HVS (g) compared to electronic imaging pipeline elements (b-f)

As with preceding experiences, which were retroactively named 'Standard Dynamic Range' or SDR, it is crucial that all the pipeline elements illustrated in Fig. 1 are working well together in order to achieve a consistent experience as desired by manufacturers and content providers alike. However, the complexity to achieve this consistency has increased significantly. The technology that is generally named HDR is composed of several changes to existing ingredient elements such as extension of displayable peak and minimum luminance levels, increased bit depth, wider color gamuts and changes in the tone-response curves, to just name a few. In addition to HDR, other technologies such as higher resolution and framerates are further adding complexity to modern image pipelines and displays.

These changes to existing ingredient elements as well as how they are implemented in modern displays pose a multitude of new challenges when assessing or calibrating displays as well as the source devices that drive them with a signal. Those changed methods typically depart significantly from the methods for traditional SDR imaging pipelines described in the IDMS. Therefore, in order to reflect HDR imaging system assessment correctly, the ICDM has decided to add a new chapter to the IDMS, Chapter 20. In order to remain focused, the information in Chapter 20 is presented in a

⁵ Adaptation of the Human Visual System (HVS) is very important to consider: At any given moment of time, the HVS can only process a small luminance range, which can be referred to as "steady state" range as indicated in Figure 1(g). To reach the full luminance range covered by night and day vision in (g), the HVS can shift its sensitivity through processes called light and dark adaptation. Adaptive processes can have a significant impact with HDR imaging, but the perceptual processes involved are beyond the scope of this tutorial. Please refer to [McCann 2011, Fairchild 2013, Dufaux 2016 and Bertalmío, 2019] for more information on this topic.



succinct and purposeful fashion and is therefore not intended to provide context or further details on how HDR metrology connects to the larger HDR ecosystem.

Even though this deliberate choice helps with clarity and conciseness of Chapter 20, it is beneficial to a metrologist to understand the fundamental concepts that form today's larger HDR ecosystem before embarking on the quest to characterize and calibrate displays that have HDR capabilities. In order to aid with this goal, this tutorial presents and discusses the fundamental conceptual and technical changes and improvements that have been introduced with the advent of HDR technologies. Those fundamental changes are then compared to traditional approaches and how they affect efforts related to display and imaging pipeline characterization and calibration. This tutorial is therefore intended as a companion document to Chapter 20, and it serves as a reference to raise awareness of the before-mentioned complexities when conducting metrology on modern electronic information displays.

Ultimately, the approaches described here as well as in the HDR metrology portions of Chapter 20 can help establish a well-behaved HDR imaging and display ecosystem so that the HVS, which is the ultimate recipient of the displayed imagery, can perceive the best possible image intended from a given source signal and display.

B33.3 Terminology and Scope of HDR Concepts

Before starting with this tutorial, it is important to emphasize the following: The longer HDR technologies have been in the market and with that a focus of research and development, the more fields implement its theoretical aspects and underlying technological concepts. HDR concepts have found many use cases in different fields and applications. Even though those fields are often adjacent, the underlying attributes that define the HDR experience can vary. In context of an imaging pipeline, those fields typically start with content capture or computer graphics (CGI) modelling, and continue with post-processing, special effects, editing & color grading, each of them using HDR-related techniques that help improve the image quality and ultimately improve the options viable for storytelling or the general visual display of information.

The actual implementation of HDR techniques can also vary in the context of different use cases. The expectations and requirements for professional motion picture content creation in HDR may be different from the ones for still photo editing [Reinhard 2010], image-based lighting (IBL) used in computer graphics [Bloch 2010], or content consumption on consumer TVs, just to name a few examples. It is therefore crucial to identify what aspect of the HDR imaging ecosystem affects the ultimate image presented on a display.

Further, as the needs and requirements amongst those different fields vary, the aspects about HDR that are, for example, crucial versus optional, or maybe not important at all, also vary greatly. For example, the field of broadcast engineering often has different requirements than the movie industry. Further, emphasis on how and to which accuracy level HDR concepts are implemented can vary based on the target audience. This diversity of understanding can lead to a diluted meaning and scope of terminology when communicating definitions and concepts in the context of HDR imaging. For example, the available definitions on what the common terms 'HDR' or 'Metadata' encompass is very broad. It is also common that the same HDR imaging related concept is known by different names in different fields. To complicate things even further, the scope of those names might vary, sometimes significantly. An example is the term "tone mapping" or "tone reproduction" (discussed in section B33.7 below) which originated in academic HDR imaging [e.g., Reinhard 2002, Schlick 1994]. It was adopted by the content and display industries to refer to pixel and image manipulation that is mainly perceptual in nature (preserving the intent of the content). The term "rendering intent" that is common with the color gamut and color management engine field extends the scope of the term "tone mapping" by also including colorimetric approaches that, for example, are implemented to simply clip or crush a signal (tone-mapping concepts are explained in detail in section B33.7). Also, tone mapping does not always have to refer to a reduction in luminance but can include any signal level modification. Therefore, when communicating concepts related to HDR technologies, it is crucial to verify that the scope and fundamental concepts indeed reflect the intent of the communication. The ICDM is not attempting to judge the different approaches but wants to raise awareness that there indeed exists the likelihood of miscommunication if one is not factoring in such different perceptions on HDR imaging concepts.

Please further note that the information in this tutorial is for educational purposes only and not intended to make any suggestion about the ultimate performance of any particular display type, model or manufacturer.

B33.4 Modern Image Display

Due to the before-mentioned risk of misunderstanding, and similarly due to the increased complexity of the topic, discussing fundamental aspects of HDR image processing and HDR displays, and how these aspects, for example, differ from legacy imaging approaches, is beneficial before proceeding with HDR-related metrology and display assessments in particular. Further, throughout this document, the focus lies on HDR imaging pipelines in the context of electronic display metrology. Therefore, in the subsequent sections, the reference to HDR imaging pipelines solely refers to this scope as illustrated by Fig. 1 (d-f). The front-end components of imaging pipelines that, for example, include image capture, computer generated imagery, and post-processing also implement HDR methods and technologies. However, those areas are out of scope of this tutorial. Please refer to the continuative literature listed in section B33.10 in this tutorial for further information.



In the context of HDR display metrology, three main components can be identified: The image signal, tone mapping, and the behavior of the actual display hardware. This subdivision is beneficial as typically, each of those three aspects have a significant impact on the potential image output.

The first aspect in context of a typical imaging pipeline progression addresses the **image signal**, which is discussed in section B33.5. Typically, an image signal encodes the intensity levels that define the luminance range as well as the signal quantization and non-linear distribution. If more than one channel of intensity levels is present, it is also possible to encode color properties. Besides the intensity levels, the image signal also contains additional information, which is typically called **metadata**. This metadata describes fundamental properties of the signal but also aspects of the imagery that e.g., are of statistical nature and can be used to guide how a display device interprets the intensity and color values in the image signal.

The image signal describes what should ideally be displayed, that is, on a theoretical display that is able to realize the signal in its entirety without error. However, this is likely not possible with a real display device and therefore, the second aspect to consider is a process called **tone mapping**. Tone mapping typically describes how the input signal values can be re-mapped to closely match a smaller dynamic range, e.g., within the display's capabilities. This process, discussed in section B33.7, is important as the source signal often offers a larger dynamic range and wider color gamut than a target display.

The third aspect, discussed in section B33.8, considers the **properties and behavior of the display hardware**. This includes a display's control system that actively influences the display behavior in order to keep power consumption, thermal issues, and any other adaptive behavior under control. Typically, the tone mapper and the display control system are combined in the actual display. However, there are also implementations where the tone mapping is carried out on an external device such as a video-processor, set-top box, games console, dedicated computer, or even via cloud computing. At this point, it is also beneficial to differentiate another fundamental aspect: displays are not inherently 'HDR' by default. As much as the term 'HDR Display' is in common use, the term itself does not typically reveal if a display's performance envelope is extended. Instead, it could simply mean that the display can receive an HDR signal even if its performance envelope is not significantly better compared to legacy display systems. Further, if the performance envelope is indeed extended, the improvements might also be of benefit when displaying legacy content. Therefore, instead of using the term 'HDR display', this tutorial differentiates between legacy versus modern display systems by referring to modern displays as being capable of receiving a 'Display-referred'⁶ signal.

If accurately aligned and calibrated, those three aspects of image signal, tone mapping, and display properties have the potential to provide stunning HDR image fidelity. However, the flipside of having an advanced HDR imaging pipeline is that the complexity of how all this can be facilitated has increased substantially. In order to reduce this complexity, several **signaling deployment and distribution formats** have been introduced that cover one or more parts of an HDR imaging pipeline. As with SDR signals, those formats enable the interplay of devices, particularly from content source to the content consumer. It also enables facilitation amongst device capabilities, manufacturers, and differing model years. This is discussed in section B33.9.

It is also important to mention that it is possible that not all segments of an imaging pipeline are HDR: One might encounter setups where legacy technologies are mixed with modern ones by using conversion methods between segments. For example, an HDR signal might be tone mapped for display on a legacy SDR display or picture mode. Also, legacy content might be extended to provide aspects typical for HDR imagery.

Fundamentally, a metrological display assessment needs to factor in all the above complexities of modern information displays and image pipelines and determine the individual characteristics individually without having them influence each other and potentially alleviate or eliminate any biases to image fidelity, for example, by applying calibration.

B33.5 HDR Signal

As introduced earlier, an image signal that can fundamentally be considered as being of 'higher' dynamic range has to be able to transport an extended signal that provides more luminance information (visible as brighter whites and highlights as well as more shadow detail). This is usually connected with offering a larger color volume (visible as more pure and brighter colors⁷). Also, as we are dealing with a digital signal that by definition is quantized, it is important that the quantization does not cause any visible artifacts that deteriorate the image quality, neither in the darks, mid-levels, nor higher-intensity signal levels.

Further, the fundamental HDR signal does not describe perceptual concepts that for example, directly or indirectly, describe if a signal level appears at a certain lightness or darkness or how chromatic it is. With SDR signals, the chances that low and high signal values align with stimuli perceived as dark and bright, respectively, are relatively high. With HDR

⁶ A display-referred signal represents the intent of the content creator. A display-referred signal requires a definition of non-linearity, min/max luminance, and the color encoding of the signal container. The encoded signal values can be directly transformed to absolute values. Further detail can be found in IDMS chapter 20.

⁷ Fundamentally, although chromatic components are often addressed as being part of an HDR signal, an HDR signal may only refer to luminance levels. The reader should verify this aspect when considering HDR standards or formats.



signals on the other hand, such assumption does not necessarily hold true. One perceptual concept that is particularly important to accurately consider is how to address perceptual elements that are perceived as brighter than diffuse white (also often called ‘reflective white’, as this term describes the light reflected from a white surface) such as light sources, highlights, and reflections that are depicted in an image⁸.

To factor in and facilitate all the above considerations, new signal properties and formats have been created that have enough bandwidth and granularity to transport HDR information effectively and enable imagery to incorporate the before-mentioned perceptual elements. The properties and how this granularity is achieved are the content of the following sub-section.

Please note that from a perceptual point of view, it is not possible to define where the threshold between what is referred to as SDR vs. HDR lies. Even though there are definitions brought forward by other standardization groups (see section B33.9.7), it is not the purpose of the ICDM to provide such judgement. Nevertheless, a valid assumption of HDR in the context of content display is if a display device or element of an HDR imaging pipeline can recognize and work with valid HDR image formats.

B33.5.1 Fundamental Properties

The main objective of an electronic information display is to generate light emissions in an orchestrated fashion, typically by spatially but also temporally modulating this light emission. This is done in a way so that the Human Visual System (HVS) can gain comprehensible but also meaningful or pleasant information when observing the information display.

The information on how the light intensity emanating from the display should be modulated is provided by an image or video signal. In order to generate the before-mentioned comprehensible, meaningful, or pleasant imagery to the HVS, it is beneficial to establish a correlation between signal and light output. In the case of an electronic display, the SI measure of luminance is used to quantify how much light is emitted by a display. Luminance is a photometric measure (based on the spectral sensitivity of the human visual system) of the luminous intensity per unit area of light travelling in a given direction. The unit of luminance is the candela per square meter or cd/m^2 . Further, a common synonym for the SI unit cd/m^2 is a ‘nit’ (plural ‘nits’) which is regularly used interchangeably in the context of HDR display and HDR ecosystems in general.

The **SI unit of luminance** is the cd/m^2 ; the use of the “nit” has been deprecated, but informally use of the “nit” still persists. However, there are several other units that describe the achromatic properties of ‘light or dark’. There are typically fundamental but sometimes subtle differences that must be considered. Therefore, care has to be taken to use those units in the scope of their defined application and typically conversions have to be carried out that often require additional information in order to succeed accurately. Examples are brightness & lightness (color appearance correlates [Fairchild 2013]), luma (broadcast engineering [Poynton 2012]), and intensity (fundamental property with SI units of cd or lumens/sr). Another unit that is commonly in use in the context of projection systems is the Imperial unit⁹ of luminance, foot-Lambert (fL), which can be converted to SI luminance by $\text{cd/m}^2 = \text{fL} \times 3.426259$. Also, there are deprecated units of luminance such as the stilb (equal to one candela per square centimeter or 10^4 cd/m^2) or some historic definitions of brightness before the SI-derived measure of luminance was established. For more information on photometric units, please refer to IDMS tutorial B1.1.

It should also be mentioned that luminance is not the only SI measure that is related to light. There are several more that can be useful to metrological applications. One of those SI measures is illuminance with its unit ‘lux’, which is lumens/m^2 . Illuminance describes the lumens per unit area incident on a surface. It often is used to characterize ambient light falling on a display (refer to IDMS sections 3.5.2, 11.9, 11.10, and A3.1) and projection of light onto a screen. Figure 2 illustrates the difference between illuminance (a) and luminance (b). The light emitted by the display (here from a mobile phone) can be described as luminance in cd/m^2 when measured by a directional light meter. The incident light that is ‘hitting’ the display surface is illuminance in lux (lumens/m^2). This can be further separated as having a direct component, here

⁸ Report ITU-R BT.2408 ‘Operational practice in HDR television production’ defines the HDR reference/diffuse white to 203 cd/m^2 . However, this luminance level represents a recommendation to simplify and align interoperability in production environments and does not necessarily reflect the perceptual behavior of the HVS.

⁹ Imperial units are often confused with “English units,” but England now uses the SI units. It is better to say “Imperial units.”



originating from the lamp, as well as an indirect or diffuse component originating from the whole surround. Both incident light types are measured in lux.

Multiple individual signal values (such as pixels) can now be spatially grouped together, e.g., ordered in a matrix to form a more complex image signal. The individual signal values in such an image matrix do not have to be equal. In fact, if they are the same, it is only possible to depict featureless stimuli. Now, the variation of signal values gives rise to the concept of contrast (please also see IDMS section B20), which is in its simplest form the difference between the highest and the lowest value. Another concept to describe contrast is 'dynamic range'. The IEC International Electrotechnical Vocabulary 702-04-23 [IEC Electropedia] describes the fundamental concept of dynamic range (of a signal) as 'The difference [...] between maximum and minimum signal levels [...]'. In the context of displaying a set of light levels forming a spatial description of an image, dynamic range can be describing as the ratio between the maximum and minimum light intensities displayed as optical luminance levels.

This concept is also valid when discussing light levels encoded in an image signal. However, even though an optical light output is typically measured as absolute luminance, it is possible to describe image signals in both a relative or absolute manner. With a relative signal, the individual code words are not directly correlated to luminance and the definition of which code word relates to a luminance level is defined by components in the imaging pipeline such as the output device calibration, the image processing, and the capability of the actual display. Absolute values on the other hand have a direct correlation to luminance. Therefore, it is possible to convert an arbitrary code value to its corresponding absolute luminance value or vice versa by using the appropriate conversion function.

It is common to colloquially call images with little difference between highest and lowest luminance as 'low contrast' or 'low dynamic range'. Similar, if the difference between the two extremes is larger, images are referred to as offering a high contrast or high dynamic range. As discussed earlier, it is not possible to fundamentally define the difference between different dynamic ranges as there is no threshold separating a continuous range of possible contrasts. Nevertheless, for practical application, high level concepts were established to differentiate low and high contrast. This differentiation led to the establishment of the widely used term **HDR** as acronym for **High Dynamic Range**. The contrasting opposite to HDR can be referred to as **Low Dynamic Range** with its acronym **LDR**. Even though LDR found use in some fields such as still photography, the term **SDR** is more established in the display and content production field. Please note that commonly the scope of what the terms HDR and SDR encompass is wider than just a description of signal or light output dynamic range. This reasoning will be elaborated and extended further throughout this tutorial.

To better illustrate the foundational concepts between LDR and HDR, Fig. 3 provides an example showing a scene with a beach at night. This scene is depicted in three typical format representations. The scene itself describes high luminance highlights (the active illumination through lamps, etc.) as well as areas with medium levels of illumination (the lawn, trees and close-by beach). It also contains another beach in the background that lies completely in the dark. Together, these three image regions span a large luminance bracket¹⁰ reflecting the luminance range encountered in the actual real physical scene.

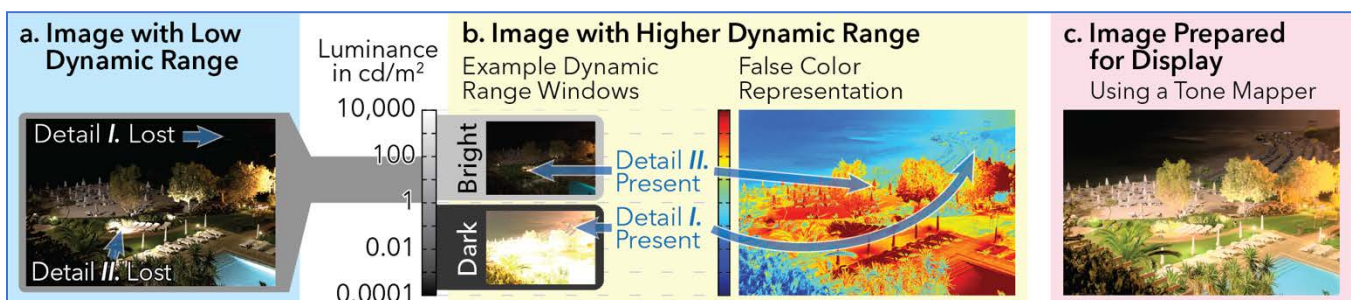


Fig. 3. High level concept between an image represented in LDR/SDR (a) vs. one in HDR (b). The example in (c) provides a preview of detail preservation when using a tone mapper to reduce the contrast from HDR to LDR/SDR as discussed in section B33.7

¹⁰ Please note that the illustration presented here is of low dynamic range due to the technical limitations of this document. However, the source HDR image indeed reflects the described luminance values.



However, such a scene is challenging to depict faithfully with a signal format that is designed for lower dynamic range (e.g., around $3 \log_{10}$ orders of magnitude). Such a case is given in Fig. 3(a). Here, the mid-tones are well reproduced. However, it is also visible that detail both in the deep darks (Detail *I*) and the highlights (Detail *II*) is lost in the signal. Now, when using a format that can cover a higher dynamic range, as shown in Fig. 3(b) (both as dynamic range window examples and luminance false color representation), the mid-tones remain well reproduced. In addition, there is also detail present in the darks (Detail *I*) as well as the highlights (Detail *II*). The final case given by Fig. 3(c) shows the HDR image after its details have been re-adjusted to remain visible, even when intended for display with a lower dynamic range than the source image (see section B33.7 for more detail on this process).

B33.5.2 Dynamic Range, Quantization and Non-linearities

So far, the discussion of dynamic range or contrast has been conceptually on a high level. To understand the particularities of how to facilitate contrast and dynamic range within the field of electronic information display and apply that knowledge to metrology, additional key concepts have to be discussed and brought into context.

One key principle to recall is that most modern electronic information displays are digital systems. For a digital system to approximate continuous values is to quantize them through binary statements. However, a single binary statement, or bit, can only encode two states (which could, for example, be mapped to a distinct ‘black’ and ‘white’). This is not sufficient to faithfully approximate the continuous nature of shades and subtle differences of light and color values required to forming an image¹¹. A solution is to combine those bits into groups. This grouping can also be called the **bit depth** of a particular encoded value. With this approach, it is possible to increase the number of distinct values that can be encoded between a minimum and a maximum value.

A complex question is: how many bits are required to faithfully reproduce an image? This leads to another question: The importance of establishing a meaningful correlation between luminance values with a given dynamic range and how to digitally address this range, using a group of bits. Even though regularly discussed and addressed individually, the maximum dynamic range achievable by an imaging system and the system’s bit depth are often intertwined. For example, it is possible to cover a dynamic range of $10^6:1$ with just 8 bits, or conversely to address the dynamic range of $10:1$ using 16 bits. Neither of these would be pragmatic, though. The low bit-depth but high dynamic range signal would suffer from visible contour artifacts (also known as staircase or ring artifact), and the high bit-depth but low dynamic range display would afford many quantization steps that are ultimately not visible to the HVS. The former display wastes its dynamic range, and the latter display wastes its bits. It is thus clear that there needs to be a balance of dynamic range and bit depth. In order that an image signal should be able to faithfully encode an increased dynamic range, there needs to be an accompanying increase in bit depth. The increased bit depth is needed in order to prevent visible false contours and other quantization artifacts.

In order to assess how many quantization steps and accordingly how many bits are ideal to strike the balance between image fidelity and signal efficiency, it is important to identify a meaningful quantization interval. As the application is to display images that are ultimately

perceived by the HVS, quantization intervals are modelled after the smallest luminance interval the HVS can distinguish. Those intervals, or deltas, are called **Just Noticeable Difference**, or **JND**. Figure 4 elaborates the concept of JNDs on a high level using two patches *I* and *II*. In case (a), the luminance of the two patches is measured to be identical. As expected, in this configuration, both patches appear the same to the HVS. In (b), the luminance of patch *II* is increased by a small amount. This change can be identified by a physical measurement, reporting a delta between *I* and *II*. However, the HVS still perceives both patches as the same because the delta is still below the visual threshold. Finally, in (c), the luminance of patch *II* is increased further: the HVS is able to perceive a difference between *I* and *II* and with that, the visual threshold of seeing the patches as different has been surpassed. That threshold is referred to as a single (one) just noticeable difference (JND).

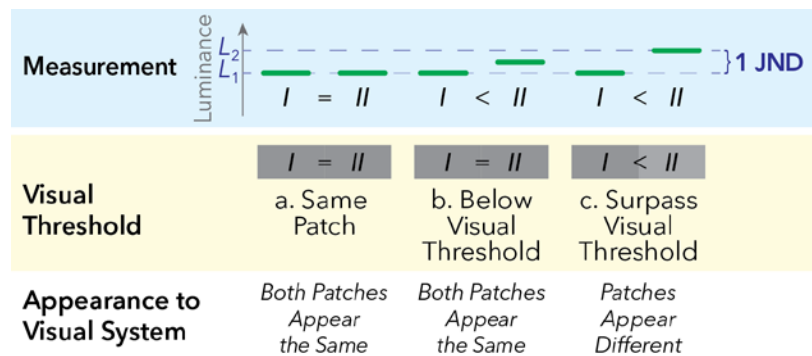


Fig. 4. High-level illustration of the perceptual concept of a just noticeable difference (JND).

¹¹ Tone scale granularity can be approximated via spatial or temporal dithering, even with a single bit per pixel. However, such an approach will inevitably lead to other disadvantages such as loss of spatial or temporal resolution.



Another aspect to consider is that the sensitivity of the HVS to luminance intervals is not a constant, equal interval distribution¹². Therefore, in order to align the signal to the efficiency of the HVS at any¹³ luminance level, it is important to consider quantization (JNDs) in context of the distribution of the quantization intervals over the full dynamic range of the image reproduction system or format. (The reader should note that such a distribution is not necessarily the capability of an actual display). This distribution is not linear and therefore is called **'tone-curve non-linearity'**.

Figure 5 illustrates the effects of quantization as well as quantization non-linearities on a high level based on a tone value 'ramp' complemented by scanline plots. All three ramps have the same relative minimum and maximum. However, the number of steps, or granularity, in between those extremes varies. Figure 5(a) quantizes with only 1 bit, which is only sufficient to encode the two extremes and not intermediate tone values. The next example in Fig. 5(b) illustrates the appearance of the same ramp, encoded with a low bit depth¹⁴. Here, more tone-values are visible between the extremes. However, due to the bit-depth limitation, contouring steps are very pronounced. The last example in Fig. 5(c) illustrates the ramp encoded with a larger number of bits, which results in the appearance of a continuous ramp without any visible contouring artifacts. In addition to illustrating the impact of the quantization intervals via the bit depth, Fig. 5 also shows the impact of a tone-curve non-linearity. Such a non-linearity has no effect on the 1-bit example as it does not impact the value extremes. However, for the other two cases, it is visible how the progression of the value ramp changes.

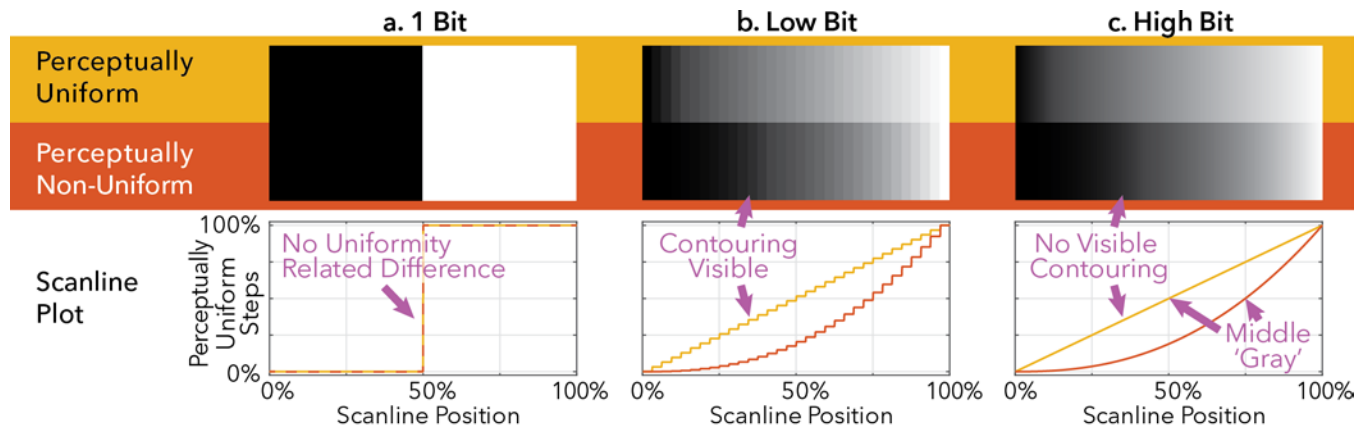


Fig. 5. Impact of quantization using different bit depths as well as perceptually uniform and non-uniform signal encoding.

¹² This tutorial focuses on the aspects of HDR that are immediately related to metrology. For more in-depth information on the perceptual and vision science side of this topic, see [Fairchild 2013, Kunkel 2016, Bertalmío 2019].

¹³ Typically, there are technical and system limits with imaging systems. But they could be changed if the necessity arises and are therefore not a fundamental limitation.

¹⁴ For this kind of illustration, actual bit depths are not used, as their actual granularity cannot be reproduced in a document.

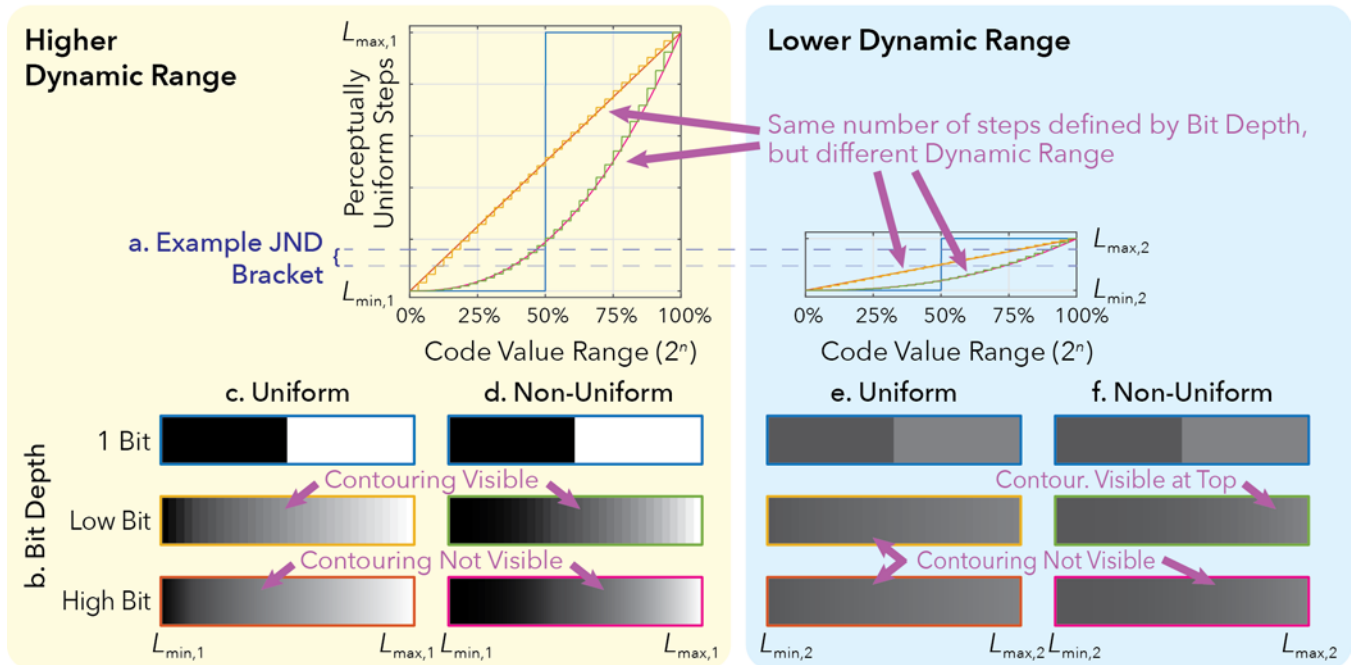


Fig. 6. Relationship between dynamic range, bit depth, and tone curve non-linearity. Note that brightness levels in the lower half of this illustration are scaled for print reproduction and therefore appear dimmer than on an actual HDR display.

Figure 5 only illustrates two of the three before-mentioned factors: The effects of bit depth and non-linearity based on relative luminance. As an emissive electronic display has a definable absolute luminance range¹⁵, the bit depth and the non-linearity have to be brought into context of absolute luminance. This is illustrated by Fig. 6, which takes the relative bit depth and non-linearity examples provided in Fig. 5 and normalizes them between two absolute dynamic range brackets. The first example on the left depicts how the single, low, and high bit example ramps appear when normalized¹⁶ to a higher dynamic range. The number of quantization steps, as defined by the bit depth as well as their uniformity, as defined by the non-linearity, are distributed in an absolute manner between the luminance extremes defined by $L_{min,1}$ and $L_{max,1}$. This means that there is now a straight correlation between signal value and associated absolute luminance. Here, the just noticeable differences (JNDs) as discussed earlier come into play: As each quantization interval can be correlated to absolute luminance, it is possible to determine if there is a sufficient number of bits to keep the quantization intervals below a JND for each step. In the case of the low bit example, the quantization intervals for the given luminance range of $L_{min,1}$ to $L_{max,1}$ are larger than JND steps, therefore, contouring artifacts become visible. This can be remedied by assigning more bits for this luminance range, which leads to a higher number of quantization intervals, or granularity, between $L_{min,1}$ and $L_{max,1}$. This is again illustrated with the high bit example where the quantization intervals are smaller than JND intervals such that contouring effects are not visible.

The second luminance bracket, shown on the right side of Fig. 6, represents a lower dynamic range spanned by $L_{min,2}$ and $L_{max,2}$. If the same single, low, and high bit example ramps are normalized between this luminance range, the appearance of the ramp is different. The obvious difference is that the contrast between the minimum and maximum luminance is significantly reduced, which is illustrated by the light and dark grey patches in the 1-bit example. At the same time, as the same amount of quantization intervals are distributed over a smaller dynamic range bracket, contouring is avoided, even with the low bit example, as now the quantization intervals are smaller than the detection threshold of the HVS. The two dynamic range examples can be compared by the example JND bracket given by Fig. 6(a): The luminance bracket remains the same, but the lower dynamic range example ends up with more quantization intervals in the given bracket than the higher dynamic range example. However, even though contouring artifacts are avoided by normalizing to lower dynamic range, there might be too many quantization intervals. This is not an issue with fidelity but might lead to inefficiencies, e.g., when encoding a signal as quantization granularity is encoded that can never be distinguished by the HVS and thus can result in wasted bandwidth.

¹⁵ In a typical display device, this absolute luminance range can be variable to some extent and be limited either physically or by software such as through picture mode settings. Those concepts are discussed further in section B33.8. Ambient light can also impactful, which is discussed in section B33.9.3.2)

¹⁶ Please note: Although fundamentally viable, signal normalization is not necessarily desirable to map tone values. This topic is discussed further in section B33.7.



As introduced in Fig. 5, the signal non-linearity has to be considered and ideally follow the detectability thresholds of the HVS for the given absolute luminance range. Otherwise, it is possible that contouring artifacts could become apparent over certain parts of the luminance range, even though there are apparently sufficient quantization steps available. This is shown in the low bit gray ramp in Fig. 6 (f). Here, sufficient quantization steps are available in the darker luminance range as the tone-curve non-linearity is shallow. However, for the portion of the tone scale that is lighter, contouring steps become visible because the quantization steps are larger than the detectability threshold.

B33.5.3 HDR Transfer Functions and EOTF

As established already, with electronic information displays, an encoded image signal is typically intended to be rendered to an electronic display that outputs light. For this, the encoded signal has to be decoded into a linear luminance signal first, which is facilitated by a non-linear transfer function. This non-linear transfer function is called an **electro-optical transfer function**, or **EOTF**. In particular, an EOTF describes how to convert from the non-linear signal encoding (referred to by the ‘electro’) to linear ‘light’ output (‘optical’)¹⁷. Similarly, when encoding linear light into a signal (e.g., for a camera), an **opto-electrical transfer function** or **OETF** is applied.

One important aspect for making non-linear approaches practical in imaging pipelines is the knowledge of the properties of a particular signal’s OETF and EOTF. With that information, linear light can be encoded with a well-defined non-linearity (OETF), then further downstream in the imaging pipeline be decoded and undone again by using an inverse transform (EOTF). It is also possible that the EOTF does not describe the exact inverse of the OETF, either deliberately or unknowingly. If it is deliberate, then the difference between input and output linear ‘light’ can be described by an overall optical to optical transfer function (OOTF) that results in a displayed image that intentionally does not match the scene luminance levels (not even proportionally). For further information, please refer to [ITU-R BT.2100, Miller 2012, Dufaux 2016 & Bertalmío, 2019].

The term EOTF has found widespread use with the advent of HDR imaging but is not limited to the realm of HDR. For example, gamma non-linearities that have been commonplace with electronic imaging for many years can also be referred to as EOTFs (for example, the ITU-R BT.1886 refers to its non-linearity as EOTF).

In order for an EOTF to both provide sufficient granularity (avoid contour steps) and at the same time remain efficient (avoid waste of signal bandwidth) throughout its range, an EOTF has to follow certain properties. As explained in the previous section B33.5.2, one prominent design philosophy is to match the EOTF to the detectability thresholds of the HVS. With SDR, the quantization to a gamma of approximately 2 is matched to the detectability thresholds of the HVS. This is supported by the ITU-R BT.1886 EOTF for television, which is often said to be perceptually uniform if applied correctly as defined in the standard¹⁸. This was substantiated by ITU-R report BT.2246 on Ultra-High Definition Television (UHDTV). This report used a scaled version of the model of contrast sensitivity devised by Barten [2004], which is now commonly called the ‘Barten Ramp’. Additionally, an alternative threshold function by Schreiber [Schreiber 1992] was used¹⁹ to illustrate how the ITU-R BT.1886 EOTF for HDTV behaved similarly to human perception and was near or below visual detection thresholds for signal implementations with 10 and 12 bits. Although this is roughly the case for a gamma curve with a peak level of 100 cd/m², when higher peak luminance levels are used, the 12-bit gamma curve quickly rises above both the Barten and Schreiber thresholds, suggesting that it will become likely to show visible quantization artifacts, especially at the dark end of the luminance range [Miller 2012].

In conclusion, when using higher dynamic range levels, the traditional quantized gamma values no longer match the JND distribution of the HVS, and a signal encoded with 8 bits can lead to visible contouring artifacts. However, as described in the previous section, simply adding bits to a gamma encoding will not result in a signal encoding that is both efficient while at the same time remaining visually free of contouring artifacts.

One reason for this is that one can no longer assume that the viewer is still adapted to the same luminance level²⁰. Modelling the state of visual adaptation in the context an image signal with a larger luminance range is a complex topic and is a current area of active research. It requires the inclusion of both spatial and temporal properties of an image sequence and therefore cannot be facilitated by a simple EOTF alone. However, another option is to align the quantization intervals to the detection thresholds of the HVS as described in the previous section. If the bit depth and signal non-linearity are designed appropriately, it is possible to describe the luminance range between a minimum and maximum luminance with both high efficiency and without creating contouring artifacts.

¹⁷ Whether the described linear light output is actually realized depends on several other factors of the display hardware. This topic is discussed later in section B33.8.

¹⁸ It is common that this EOTF is not implemented correctly, in which case perceptual uniformity cannot be assumed.

¹⁹ The Schreiber threshold function makes the simple assumption that the HVS is logarithmic (following Weber’s law) above 1 cd/m² and has a gamma nonlinearity for luminance below that level.

²⁰ Visual adaptation describes the temporary change in sensitivity of the HVS when presented to stimuli of varying intensity. For more detail on visual adaptation, see [Fairchild 2013, Webster 2015].



B33.5.3.1 Perceptual Quantizer

In order to develop an effective EOTF following the before-mentioned properties, one fundamental question is, how to determine if an EOTF retains quantization steps that are all equal or below the threshold of one JND over an absolute luminance range. This problem can be approached by looking at it in terms of sensitivity²¹, which is the inverse of threshold. Of particular interest is the understanding of how sensitivity of the visual system varies with luminance level. One approach to answer this question is to follow worst-case engineering design principles.

Fundamentally, worst-case engineering considers the most severe possible behavior of a system that can reasonably be projected to occur in a given situation. In the context of imaging, the worst case can be defined by either contouring steps to become visible or by unnecessarily wasting bandwidth for a given luminance level. Whether any of this is the case can be identified by the crispening effect [Whittle 1986], which describes that the sensitivity of the visual system is maximized when the eye is adapted to the luminance level for which the sensitivity is needed. With this knowledge, it is possible to refine the question of sensitivity vs. luminance level of the system luminance range to sensitivity as a function light adaptation level, where those levels are constrained by the system dynamic range.

The benefits of approaching the effectiveness question through worst-case engineering design is illustrated by Fig. 7, which provides two simple real-world viewing situation examples for single (a) or multiple viewers (b), in a home or theater viewing, respectively. In example (a), the still image shown can be regarded as a frame in a movie sequence. The dark alley dominates the image area yet has a bright region in the distance as the alley opens up to a wider street. Depending on where a viewer might look, the overall adaptation level would be different. In the left illustration showing a single viewer, the viewer may look from interest area A to area B in the course of the scene, and their light adaptation would change accordingly from a lower state to a higher state of light adaptation²². Therefore, if the scene would be only rendered accurately for e.g., the lights, it might be possible that artifacts are visible when changing adaptation to the dark part of the image. The image on the right (b) depicts another common scenario. Here, multiple viewers are shown, each looking at different regions of the scene. Different light adaptation states would likely occur for each viewer at the same time. Similar to example (a), if the scene would only be rendered accurately for one viewer, the other viewers might perceive artifacts.

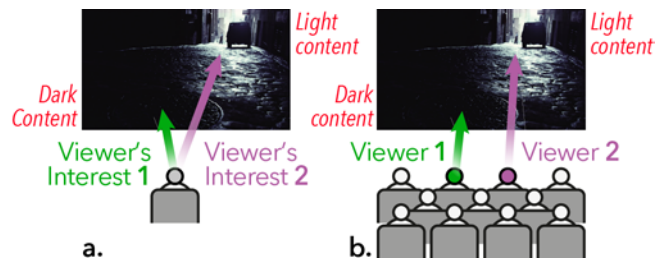


Fig. 7. Examples for single (a) or multiple viewers (b), scenarios that are common with home or theater viewing.

33.5.3.1.1 Design Considerations

The investigation on how to design new quantization nonlinearities that are more accurate than gamma is not a recent development [e.g., Lubin 1991]. In 1993, a new quantization nonlinearity based on the contrast sensitivity function (CSF)²³ was developed for medical use [Blume 1993] and used by the Digital Imaging and Communications in Medicine (DICOM) Standards Committee in the early 2000's (NEMA Standards Publication PS 3.14-2008). This curve, known as the DICOM Grayscale Standard Display Function (GSDF), is based on a model of contrast sensitivity of the eye that was developed by Barten [Barten 1996]. This 'DICOM curve', as it is often colloquially referred, can reproduce an absolute luminance range from 0.05 cd/m² to almost 4000 cd/m² without artifacts when using a 10-bit encoded signal. This standard has been used very effectively for a wide variety of medical imaging devices ever since.

²¹ Sensitivity is a common concept with Vision Science.

²² There are several effects that affect the adaptation level such as visual glare. Nevertheless, depending on the viewing geometry and temporal properties of the content, there are always scenarios where they are alleviated or eliminated completely.

²³ The Contrast Sensitivity Function describes the sensitivity of the visual system over a wide range of spatial frequencies. In comparison, Visual Acuity measures primarily sensitivity at the high spatial frequencies. For more information, see [Bertalmio, 2019, Dufaux 2016].



To increase the applicability with general image display, several improvements over the DICOM curve were considered. While the new nonlinearity was developed based on the same Barten model as the DICOM GSDF, a wider luminance range was facilitated as it was found that viewers did report benefits in psychophysical studies [e.g., Daly 2013]. Further, model parameters were adjusted for a larger field of view, which was more suitable for potentially larger displays or viewing angles as common with entertainment media consumption. Another improvement to the model calculations was CSF peak tracking [Cowan 2004, Mantiuk 2006]. The Barten model calculates an estimate of the CSF based on both luminance and spatial frequency, but it turns out that the spatial frequency, which results in the largest CSF value, varies with luminance level. While DICOM maintained a constant frequency of 4 cycles/degree for all luminance levels, the new nonlinearity was calculated while allowing the spatial frequency value to always operate at the very peak of contrast sensitivity. This concept of CSF peak tracking is illustrated in Fig. 8.

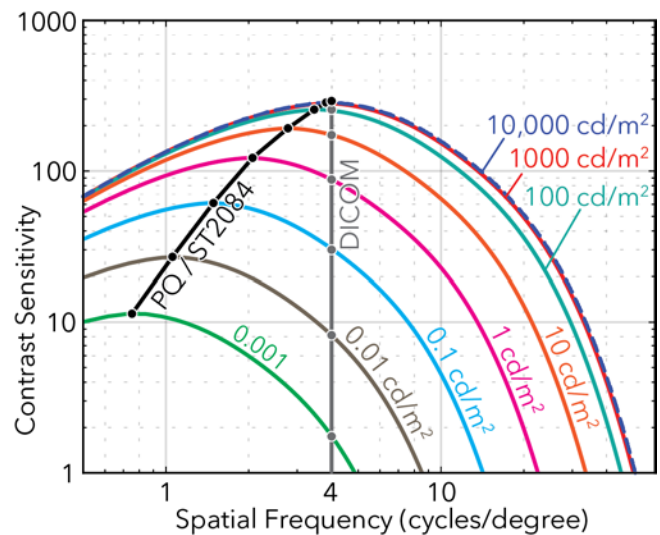


Fig. 8. Concept of CSF peak tracking over different luminance levels for PQ vs. constant frequency used by DICOM.



The resulting EOTF is called the **Perceptual Quantizer**, or more commonly ‘PQ’²⁴ [Miller 2012]. In order to maintain that the CSF peaks are tracked accurately, the PQ EOTF follows absolute luminance with a range spanning 0 to 10,000 cd/m². When quantized with a granularity of 11 bits, the thresholds per step remain under one JND throughout the luminance range.

The PQ EOTF was standardized as SMPTE ST 2084 and is also part of ITU-R BT.2100²⁵ and its parametric form is provided by

$$L = 10,000 \left(\frac{\max \left[\left(V^{1/m_2} - c_1 \right), 0 \right]}{c_2 - c_3 V^{1/m_2}} \right)^{1/m_1} \quad (1)$$

where $m_1 = 0.1593017578125$, $m_2 = 78.84375$, $c_1 = 0.8359375$, $c_2 = 18.8515625$ and $c_3 = 18.6875$. Using this equation, it is possible to convert input signal value V in the range $[0 \dots 1]$ to the output luminance L in the range $[0.0 \dots 10,000]$ cd/m².

B33.5.3.1.2 Efficiency of the PQ EOTF

To assess the performance of the PQ EOTF, it can be compared with other known methods in Fig. 9. In this figure, the x-axis describes the absolute luminance²⁶ in cd/m². The y-axis provides minimum contrast steps, which are provided as percentage over the intended luminance range and the given bit depth. As reference, the perceptual models by Barten and Schreiber are plotted as dashed lines.

Two examples using gamma are provided. If limiting the dynamic range to a maximum of 100 cd/m², 10-bit gamma is in most cases sufficient as reflected by ITU-R report BT.2246. However, to cover a larger dynamic range up to 10,000 cd/m² while at the same time guaranteeing that no artifacts can be visible, the quantization granularity has to be increased to 15 bits, as illustrated by the second gamma curve. Similarly, if encoding in log₁₀, a bit-depth of 13 would be required to effectively remain below the Barten ramp for the full desired dynamic range of 0.0 to 10,000 cd/m². However, this encoding would not be efficient, especially in the darker luminance range.

In order to effectively cover the same dynamic range, PQ only requires a quantization of 12 bits to efficiently fit below the Barten threshold curve. Quantizing the PQ curve with 10 bits is also a common option. Even though there might be occasional artifacts visible such as with noise free shallow gradients, they are unlikely with normal content. This 10-bit option is comparable to 10-bit gamma, albeit the latter only providing a maximum luminance of 100 cd/m².

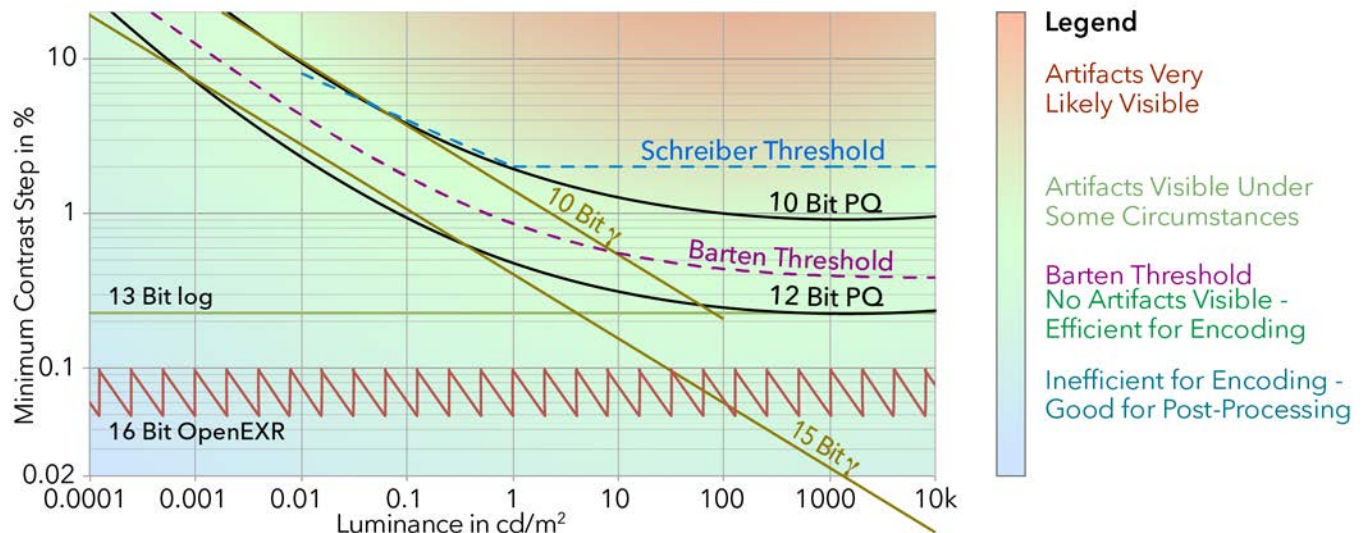


Fig. 9. Performance of various EOTFs and bit depths compared to the Barten and Schreiber thresholds and in the context of artifact visibility and potential bandwidth inefficiency

²⁴ In the scope of electronic information display, another common use for the abbreviation PQ is ‘Picture Quality’ and care should be taken to avoid confusion.

²⁵ Please note that the EOTF is typically only a part of an HDR format or protocol. There are several formats that use the same EOTF such as PQ but differ in several other properties. HDR format or protocol are discussed in section 0.

²⁶ Please note, since the visual system can operate over very large luminance ranges, many illustrations in this tutorial plot luminance based on a base10 logarithm. However, this is not to imply that log luminance is a model of the visual system.



For completeness, OpenEXR, a 16-bit floating point-based encoding format common in post-production is shown. For this use case, bandwidth efficiency is less important than to maintain the ability to modify the signal such as common with special effects and color grading.

B33.5.3.2 Hybrid Log-Gamma

The PQ specification is able to cover a very wide range of luminance levels for a given bit depth using an EOTF that is finely tuned to match the sensitivity thresholds of the HVS. However, it is not directly compatible with legacy standards such as gamma-based EOTFs used with SDR signals. In order to provide a degree of compatibility with legacy display systems, another HDR capable non-linearity has been established, which is named **Hybrid Log Gamma**, or **HLG**. The HLG non-linearity is designed to approximate the before-mentioned established television transfer curves that are e.g., based on pure gamma, while still facilitating HDR signals with increased dynamic range [Borer 2016].

HLG is a display-independent system and relies on an OOTF (see beginning of section B33.5.3) that varies based on a display's brightness and viewing conditions (the OOTF can also facilitate a rendering intent). Therefore, in contrast to the absolute luminance addressing of PQ, HLG addresses its signal range in a relative way, similar to SDR approaches. Since HLG is not designed to be display-referred, it is not suitable to use for display metrology in the context of HDR signals.

A key benefit of a signal using such an approach is that it can be manipulated using conventional SDR tools and equipment as long as they can handle 10 bits. Therefore, the only actual HDR-capable equipment required in an HLG-based imaging pipeline are HDR-capable cameras and HDR displays for quality control. Due to this property, only a single signal is required regardless of whether the target display is SDR or capable of HDR.

MOTIVATION: The fundamental approach of HLG differs from the one used by PQ. Nevertheless, the main objective of both is to reduce potential quantization artifacts while maintaining encoding efficiency. As discussed earlier, the typical SDR luminance range can be acceptably quantized by a gamma response curve, avoiding or alleviating perceivable contouring effects. However, when extending the luminance range, as is the case with HDR imaging, using a gamma curve for the whole range would lead to artifacts. Those artifacts would likely be most prominent with the luminance range of brighter reflective image areas and highlights. In order to alleviate potential contouring artifacts, the response curve needs to be optimized, which can be facilitated following the understanding that above around 200 cd/m², the threshold response of the HVS can be better approximated by a logarithmic function²⁷ (see Fig. 9). This logarithmic behavior is known as Weber's Law [Fairchild 2013, Reinhard 2010, Ohta 2005].

Based on these observations, it is viable to create an HDR-capable response curve by combining a gamma part for darker tones and a logarithmic section to represent brighter tones and highlights. This hybrid approach is illustrated in Fig. 10, comparing a traditional gamma curve against the HLG non-linearity. Further, the separation between the two parts of the HLG curve is indicated. As in [Borer 2016], the horizontal axis for the HLG non-linearity is scaled to emphasize compatibility with the conventional SDR gamma curve.

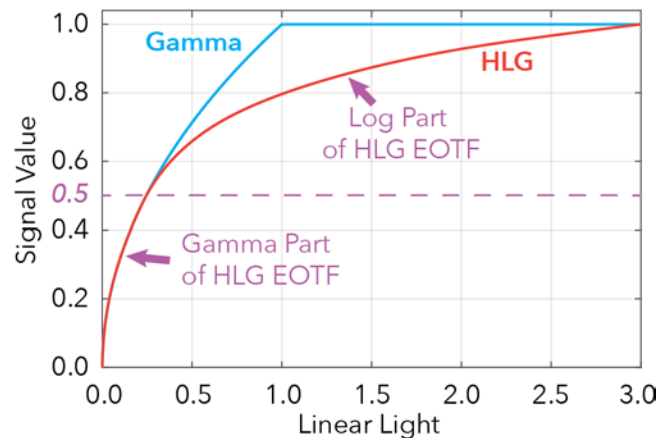


Fig. 10. Conceptual difference between gamma and HLG non-linearities; adapted from [Borer 2016].

IMPLEMENTATION: In addition to PQ, the ITU-R BT.2100 standard specifies the HLG implementation. To remain within the scope of relevance to display metrology, the equations below describe how to carry out the HLG EOTF. Please refer to the standard for full implementation guidance on the HLG OETF and OOTF. The input values to the HLG EOTF are non-linear HLG encoded values denoted by E' in the range [0:1]. Before carrying out the conversion, a set of system parameters have to be computed.

First, the luminance extremes are calculated. The parameter L_W describes the nominal peak luminance of the display in cd/m² for achromatic pixels and L_B the display luminance for black in cd/m². For displays with nominal peak luminance (L_W) between 400 and 2000 cd/m², the system gamma value is adjusted according to the formula (may be rounded to three significant digits).

$$\gamma = 1.2 + 0.42 \log_{10} \left(\frac{L_W}{1000} \right) \quad (2)$$

If L_W is outside the range 400 cd/m² to 2000 cd/m², the following alternative formula should be used (BT.2100, Footnote 2)

²⁷ There is no exact transition luminance and therefore this value is just an approximation.



$$\gamma = 1.2 \kappa \log_2 \left(L_W / 1000 \right) \quad (3)$$

where $\kappa = 1.111$. Next, the variable for user black level lift β is computed by

$$\beta = \sqrt[3]{3 \left(\frac{L_B}{L_W} \right)^{\frac{1}{\gamma}}} \quad (4)$$

Next, the black level lift is applied, which is computed by

$$E' = \begin{cases} (1 - \beta) E' + \beta, & \text{if } E' > 0 \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

The inverse HLG OETF is now provided by

$$L_S = \text{OETF}^{-1} = \begin{cases} E'^2/3, & 0 \leq E' \leq 1/2 \\ \left(\exp \left(\frac{(E' - c)}{a} + b \right) \right) / 12, & 1/2 < E' \leq 1 \end{cases} \quad (6)$$

where $a = 0.17883277$, $b = 1 - 4a$ and $c = 0.5 - a \cdot \ln(4a)$. The final luminance L can then be computed by

$$L = \alpha \cdot L_S^{\gamma-1}. \quad (7)$$

The parameter α provides user gain in cd/m^2 and represents L_W , the nominal peak luminance of a display for achromatic pixels. In order to process color imagery, each component is weighed by using the BT.2020 weighting coefficients $K_{RGB} = \{0.2627, 0.6780, 0.0593\}$ through the parameter Y_S . Please refer to ITU-R Rec. BT.2100 for more details.

To simplify deployment and due to high number of options, the implementation of the set of HLG formulas is often done with look-up tables (LUTs, BBC LUTs).

B33.5.3.3 EOTF Comparison

Figure 11 provides a comparison of three types of EOTFs: The relative HLG EOTF, the absolute PQ EOTFs, and for reference, the EOTF of ITU-R BT.1886, which follows a gamma of 2.4. The intent is solely to illustrate the behavior of the EOTF curves and the difference between absolute and relative EOTFs. It is not intended as a judgement of which EOTF is better.

The example EOTFs were computed using the reference equations from BT.1886 and BT.2100 (HLG and PQ). To enable a comparison of the different EOTFs in the context of realistic target display examples, they are plotted based on absolute luminance brackets that are in the scope of the luminance range specified in the BT.2100 standard and listed by Fig. 11(b). BT.1886 indicates a reference peak luminance of 100 cd/m^2 which was used in the example. The most common peak luminance for HLG is 1000 cd/m^2 but it is not limited to that value; therefore, peak luminance levels of 200, 400 and $10,000 \text{ cd/m}^2$ were chosen and are additionally shown²⁸. For simplicity, all minimum luminance levels in this comparison are set to 0.0 cd/m^2 .

²⁸ As mentioned earlier, the BT.2100 standard defines that for peak luminance levels that are either below 400 or above 2000 cd/m^2 , a different computation is carried out (Eq. 3) than for peak luminance levels within that bracket (Eq. 2).

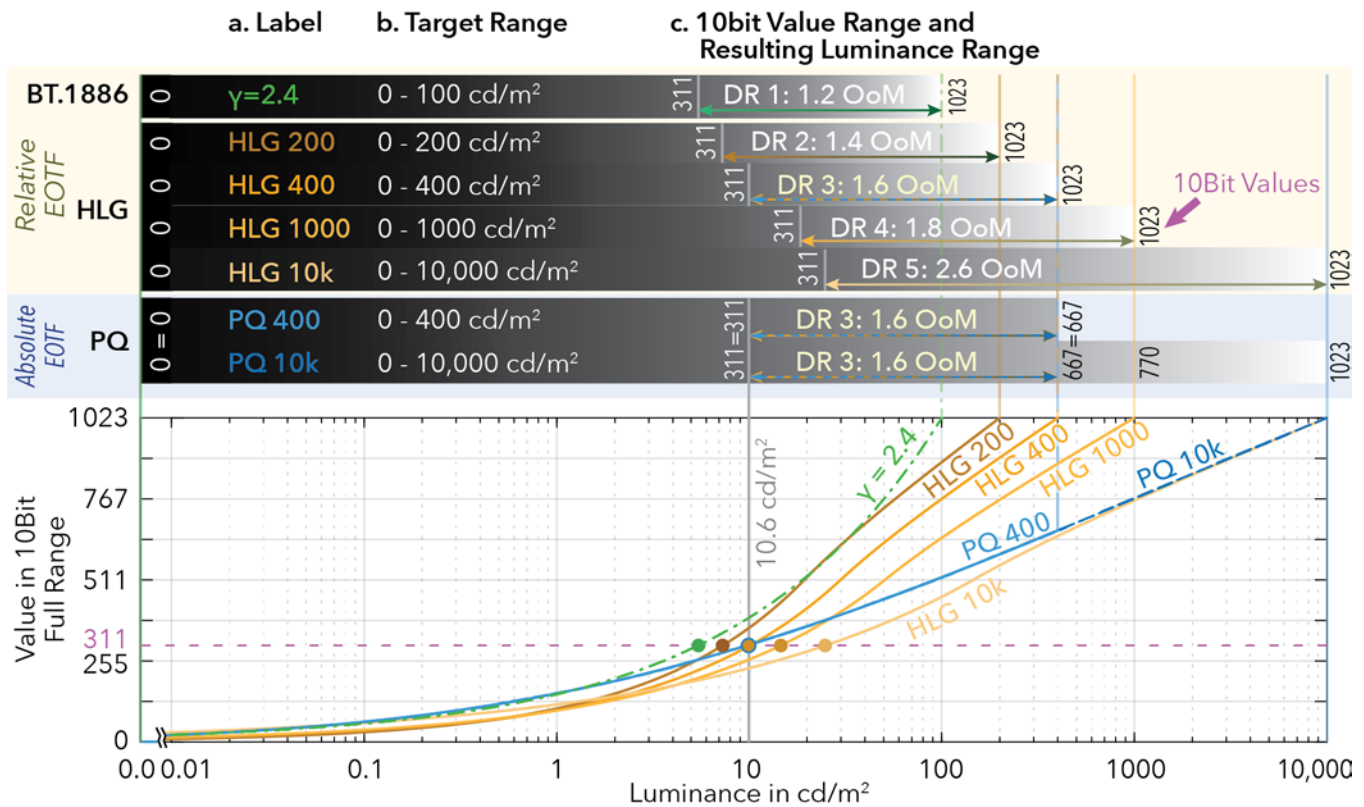


Fig. 11: Comparison of EOTFs defined by ITU-R BT.1886 and several luminance targets of HLG as well as PQ. For illustration purposes, the black level is set to 0.0 cd/m² for all curves. ‘DR’ stands for Dynamic Range; ‘OoM’ stands for orders of magnitude.

Due to their fundamentally relative nature, HLG and BT.1886 do not offer a direct relation to absolute luminance values as is the case with PQ. Therefore, the values described by the signal range (here 10 bits) are distributed over each target luminance range. This means that the maximum code word of 1023 results in a different luminance level for the 5 relative EOTFs. To provide another reference point, the code word 311 is chosen (the closest 10-bit PQ code word to 10 cd/m²). With this, the dynamic range bracket spanned between those two example code values is shown to increase based on the peak display luminance. Further, the quantization intervals are ‘stretched’ as well, which potentially can increase the risk of contouring artifacts to emerge, particularly when retaining 10-bit quantization for higher peak luminance targets such as for the depicted 10,000 cd/m² example.

On the other hand, the PQ EOTF directly relates code words to absolute luminance. PQ quantization intervals do not change and are therefore independent from the target peak luminance. Please note that tone-mapping processes are not intended to be factored in here.

B33.5.3.4 Other EOTFs

In addition to the common EOTFs described above, there are other HDR-capable formats that rely on different EOTFs. They are mainly used in content production and are mentioned here for completeness. One example is the already introduced OpenEXR format (www.openexr.com) that offers floating-point based linear light encoding. Also, camera RAW file formats or log encoding formats can facilitate HDR e.g., by exhibiting an encoding that follows the response curve of the specific capture device. Please note that RAW file formats are typically manufacturer dependent. Therefore, the reader is advised to check with the manufacturer for a detailed description.

B33.5.4 HDR Content Properties

Current HDR EOTFs such as PQ can cover a dynamic range up to 0.0 to 10,000 cd/m². However, the fact that such a large signal dynamic range can potentially be used by image pixel values does not mean that each image, shot²⁹, or scene has to

²⁹ In the context of cinematography, a shot is defined as a single, uninterrupted series of frames from a camera or rendering (also called ‘take’). A scene may consist of one or multiple shots with the same visual properties.



cover this full range. Most content will only use a part of the **total signal range**. This can be either because the captured image exhibited less dynamic range than addressable or because the source display, on which the content was prepared, did not cover the full signal range.

Figure 12 elaborates these differences based on three exemplary content frames. Item (a) illustrates the full absolute signal range from 0.0 to 10,000 cd/m^2 . Each of the frames of a content piece could contain luminance pixels within this range. Typically, the overall dynamic range is limited by the minimum and maximum luminance levels of the display that was used to create the content in the first place³⁰, which in this example ranges from 0.005 to 4000 cd/m^2 (b). In the context of HDR signaling, it is common to refer to this creation display luminance level limiting range as the **HDR ‘container’ range**³¹ (this also relates to the color primaries, which is discussed later). The container boundaries are typically signaled by metadata.

Figure 12 (c) through (e) illustrate typical scenes one can encounter with HDR imaging. Not every frame has to cover a luminance bracket that would be considered HDR by itself, as illustrated by the desert scene of Fig. 12(c).

Nevertheless, it is very bright, and with that it benefits from an HDR imaging system. Figure 12(d) shows a frame depicting an unilluminated cave that again shows a lower contrast, but it is also a very dark scene with the maximum luminance level remaining below 1 cd/m^2 . Such a scene would, again, be challenging to facilitate without HDR imaging. Finally, Fig. 12(e) shows a frame with a much larger dynamic range, from very dark pixels in the shadows of the cave, via the illuminated wall, towards the pixels depicting the lit flame.

One of the key differentiators for HDR from SDR is the ability for more accurate rendering of bright highlights substantially above a scene’s diffuse white. These can be categorized as two major scene components: specular highlights³² and emissives (also referred to as self-luminous). Even though the separation between reflective and emissive pixels is an element of image appearance³³, it is still important to consider in the context of display metrology, especially in the context of the size of a bright feature (see also section B33.8).

In traditional imaging applications, the range allocated to highlights is fairly low with the majority of the image range being allocated to the diffuse reflective regions of objects. The highlights were generally set to be no higher than 1.25x the diffuse white. Actual real-world measurements show a different picture, with highlights potentially over 1000 times higher than diffuse white [Wolff 1994]. This means the physical dynamic range of the specular reflections vastly exceed the range occupied by diffuse reflection. With SDR, the limited dynamic range and lower bit depth motivated an emphasis on allocating signal levels to reflective pixel regions over highlights. However, with HDR signals, it is now possible to allocate a significantly larger luminance headroom to highlights. HDR signaling has therefore the capability to facilitate more realistic scenes, visible depth cues, and support for the appearance of material properties such as glossiness or wetness.

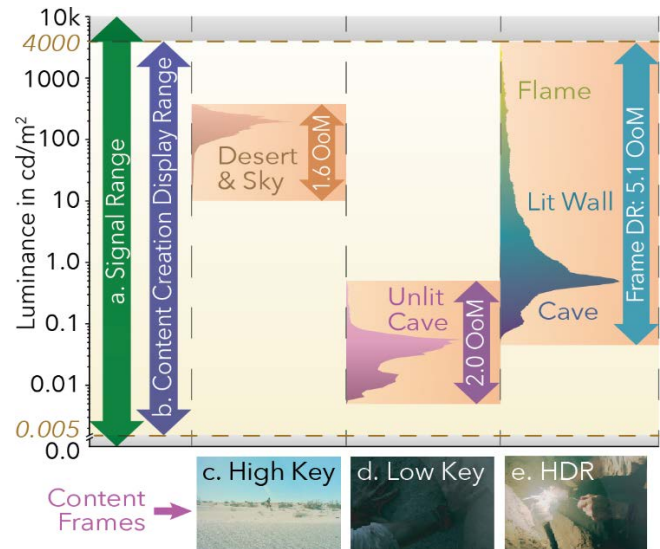


Fig. 12. The difference between signal range (a), content creation display range (b) and three different scene/frame dynamic ranges (c-e).

³⁰ Please be aware that this is not always the case as sometimes, signal values can exceed the grading display’s capabilities, either accidentally or deliberately.

³¹ Sometimes the full signal range is referred to as ‘container range’, posing risk of confusion.

³² In traditional photography, the term ‘highlights’ is sometimes used to refer to any detail near white, such as bridal lace, which may entirely consist of diffuse reflective surfaces. Here, the use of ‘highlights’ refers to the specular or emissive regions in an image.

³³ Most vision research has concentrated on understanding the perception of diffuse reflective objects, and the reasons are summarized well by [DeValois 1990] as well as [Fairchild 2013].



Figure 13 illustrates the impact that different highlight ranges can have over a constant reflective range. If sufficient highlight headroom is allocated, then the highlight in the depicted spoon supports the appearance of high gloss of the applied ceramic glaze (a). If the highlight headroom is reduced, this image's appearance changes, and the spoon appears lackluster (b). Finally, if the highlight is collapsed to the same luminance as the diffuse white, as it might happen with signal clipping, the material appearance changes from glossy to matte (c). The ability of an HDR imaging system to address and render sufficient headroom for small highlights is therefore an important HDR property.

Figure 14 provides another example containing both highlights and diffuse white elements. Please also note that in some scenes, image elements exhibit extremely high luminance levels, leading to clipped pixels, even with the maximum luminance that can be addressed by HDR signals. Examples are the sun disc or direct reflections thereof e.g., on water surfaces. Those elements are typically mapped to the maximum luminance of the content creation display by the content creator.

In addition to headroom considerations for highlights and areas that depict emissive elements, it is also important to consider that very dark image areas are encoded without signal crushing as modern HDR formats such as the perceptual quantizer (PQ) can address luminance values down to the absolute luminance sensitivity threshold of the HVS.

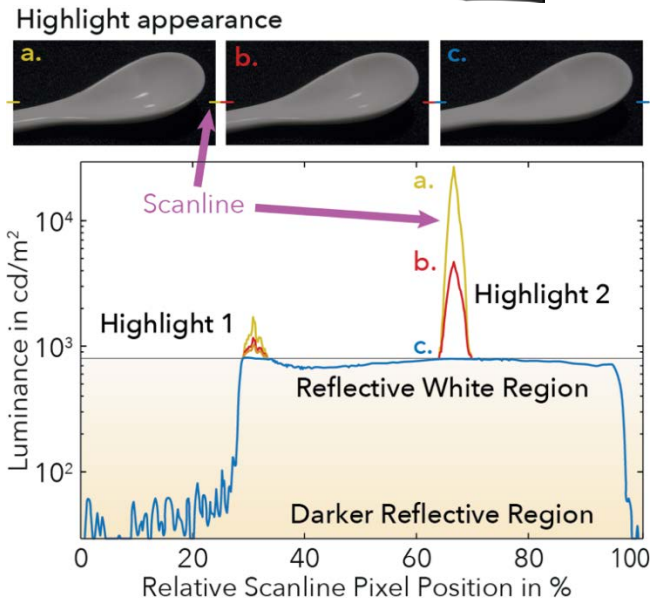


Fig. 13. Impact of different highlight ranges over a constant reflective range. In image (a), the highlight has sufficient signal headroom to support the material appearance of gloss. With less headroom, the gloss appears lackluster (b). If there is no headroom for highlights (e.g., due to signal clipping), the material property changes significantly from glossy to matte.

B33.5.5 Color Gamuts, Color Gamut Containers, and Color Volumes

In the previous sections, the main concepts of HDR signals were introduced by discussing dynamic range, quantization, and tone curves. Furthermore, the concepts of format range, dynamic range containers, and image range have been discussed. So far, all those concepts have been discussed from an achromatic point of view. However, the HVS perceives color, and it is therefore a natural consequence to include the chromatic component to HDR concepts.

HDR imaging has been able to facilitate color since its conception and the colorimetric accuracy of HDR imagery can be high when working with real-world luminance levels. Even though the concept of HDR is often understood to also include color, it is nevertheless very common to refer to the color component as **Wide Color Gamut**, or **WCG**. WCG typically refers to a color system's ability to handle color primaries that are more saturated than legacy primaries such as those defined in ITU-R BT.709. To facilitate extended color range, color spaces with more saturated color primaries have been established. Examples include DCI-P3³⁴ and ITU-R BT.2020. These newer color spaces are being used in both consumer and professional worlds. Also, color spaces such as CIE XYZ and ACES [SMPTE ST 2065-1 have found new and wider application, such as in WCG HDR content production. In combination with higher luminance levels, these wider color gamuts facilitate brighter colors that appear more saturated.

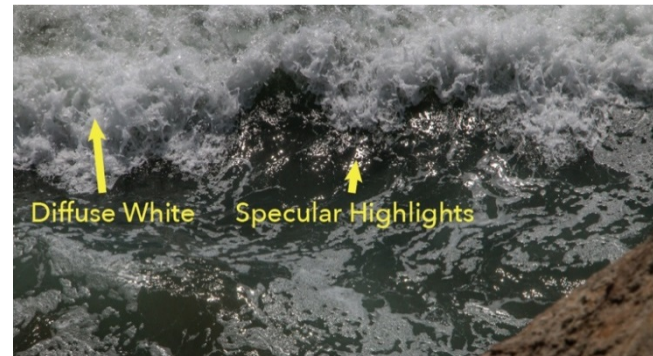


Fig. 14. Diffuse and specular reflections on water. Here, the sea spray scatters light diffusely while the water surface reflects the sunlight directly, forming specular highlights. Although both are often identified as being 'white', their actual luminance levels differ significantly.

³⁴ Please note that the white point specified by SMPTE ST 0431 differs from the D65 white point commonly used with emissive display applications. The original DCI white point is referred to as 'DCI-White', using the (x, y) chromaticity coordinates [0.314, 0.351] with a CCT of 6300K.



One often-discussed topic in the content of HDR and WCG imaging is the question of how to assess, depict, and communicate their respective properties in a meaningful way. Even though the interaction of color and intensity is a well-known fact in color science, it is still common to assess display capabilities by representing the signal capabilities through a chromaticity (gamut) area (also refer to IDMS chapter 23). A more meaningful representation can be achieved by combining this 2D chromaticity gamut with the intensity axis, which leads to a **color volume** representation. When working with lower dynamic ranges such as SDR content, steady state perceptually uniform color models such as CIELAB are very valuable and have found widespread use. This topic is discussed in depth in IDMS chapter 5. However, it is important to note that CIELAB was not designed for HDR applications and therefore, perceptual accuracy throughout large HDR color volumes that span more dynamic range than covered by the steady state dynamic range of the HVS cannot be guaranteed. Active research is currently underway to assess this aspect further. Another option is to use a detection threshold approach, focusing on micro color uniformities. One common example of such an approach is $IC_T C_P$, which was designed with HDR applications in mind and standardized in ITU-R BT.2100 alongside the PQ and HLG EOTFs. Fundamentally, the ICDM does not make recommendations as to which model to use and the value and applicability of each approach should be assessed before usage with any metrology application.

Continuing the discussion from section B33.5.4, another aspect that has become common in the context of HDR imaging is that the actual color gamut, which is, for example, defined by the source or grading display, does not have to match the color gamut extent of the signal container. This approach has become feasible due to the use of 10- or 12-bit signals providing a deeper quantization granularity to a signal container and therefore, a wide color gamut (e.g. DCI-P3) can be packaged inside an even wider color gamut container (e.g. ITU-R BT.2100) without creating artifacts.

Besides all the benefits, there are also challenges that can be encountered with wide color gamut signals. From a spectral power distribution (SPD) point of view, the extremely saturated colors in a wider color gamut can only be realized with **narrower spectral wavebands**³⁵. This is colloquially often referred to as the primaries being ‘**sharpened**’. Implementing display technologies with narrow-band primaries significantly improves color fidelity but also leads to metrological challenges, such as the need for instruments capable of making narrow-band measurements, and perceptual challenges such as metamerism effects. This topic is further discussed in section B33.8.3 in the context of actual display technologies.

Another challenge to colorimetric accuracy is that changes to tone-reproduction via a tone-mapping process are common (tone mapping is discussed in more detail in section B33.7). Simple color mapping approaches can lead to large measurable and perceptual errors. For example, basic tone-mapping approaches [e.g., Schlick 1994, Reinhard 2010] can lead to large variations regarding their output rendition and consequent appearance of a remapped HDR image. This makes the colorimetric and perceptual quantification as well as the consistency challenging. However, if the mapping properties are known or can be assessed independently, the colorimetric or at least the creative intent of a content piece can be identified or preserved.

HDR colorimetry and appearance modeling remains a very active research topic and its discussion goes beyond this tutorial. To learn more, please refer to [Reinhard 2010, McCann 2011, Fairchild 2013, Dufaux 2016 and Bertalmio, 2019] as a starting point.

B33.6 HDR Metadata

The term ‘Metadata’ has long been used in the content production, broadcast, general imaging and display fields to describe a wealth of properties provided alongside an image signal. In the context of HDR, the term Metadata has gained more prominence to describe more complex properties of a signal. However, please be reminded that the existence of metadata alone does not define how well an HDR image pipeline performs. Metadata is a concept that the Merriam-Webster dictionary defines as ‘data that provides information about other data’. Therefore, it is crucial to identify what parameters and properties a given metadata type is providing and how it can be used, for example, by a display device or a rendering node. In the context of imaging pipelines and image signals, metadata can be divided into two broad categories: Fundamental signal identification metadata and image-related metadata.

B33.6.1 Fundamental Signal Identification Metadata

Fundamental signal identification metadata provides identifiers describing the properties of an image stream such as image and signal format, resolution, color space, chroma subsampling, bit depth, image compression, image transport, etc. Fundamental signal identification metadata is typically static and applies to the full duration of the content piece. Some of those properties will typically exhibit different values than with legacy formats or protocols. For example, the bit depth and color space properties typically exhibit higher values than with standards and protocols designed for use with lower dynamic

³⁵ It is possible to design display systems that use light sources with varying spectral bandwidth which can potentially alleviate this problem.



ranges. Therefore, careful selection of the metadata properties that are adequate for the intended HDR experience is paramount.

B33.6.2 Image Related Metadata

Image related metadata on the other hand provides identifiers describing intrinsic image properties that can, for example, be used by a display or image rendering node to adjust the image appearance (e.g., via a tone-mapping process, introduced in section B33.7). Example parameters include minimum and maximum luminance, average picture level, properties of the grading display, and so on, in the form of both static metadata valid throughout the whole content piece and dynamic metadata for frame-specific image parameters.

B33.6.2.1 Static Metadata

Each parameter provided by **static metadata** is intended to be applied static or globally, once for the whole duration of the content piece (e.g., a movie). Even though this might appear very limited, this static metadata can help any processing carried out in the target display by providing fundamental statistical properties of a particular piece of content. The most common static metadata definition is provided by the SMPTE ST 2086 standard with the title “Mastering Display Color Volume Metadata Supporting High Luminance and Wide Color Gamut Images”. It defines the following parameters:

Mastering Display Metadata (MDM) specifies contextual information about the display used by the content creator e.g. to view the content during final color grading (mastering). This information includes the color space and the luminance capability of the mastering display.

Maximum Content Light Level (MaxCLL) defines the linearized value of the highest RGB component in a single piece of content. Although this value is reported in cd/m^2 , it does not represent true luminance because the value is the linearized component value and not the luminance sum of the RGB components which may be higher or lower, and it may not even be the true ‘brightest’ pixel in the piece of content. As an example, if the blue component of the signal has a level of 1000 cd/m^2 after linearizing, the real luminance in a BT.2020 container is only 59.3 cd/m^2 (see ITU-R BT.2020-2, Table 4 for RGB luminance coefficients).

Maximum Frame-Average Light Level (MaxFALL) defines the linearized value of the highest average of all RGB components in a single frame in a single piece of content. The average of all pixels in each frame is first determined in non-linear space, and then linearized to determine the MaxFALL value reported in cd/m^2 . Please note that although this value is reported in cd/m^2 , it is not calculated using luminance coefficients (see MaxCLL above), so the value is unrelated to the effective luminance – it is the linearized average of individual component values for every pixel in a frame.

How this metadata is facilitated physically, e.g., via the HDMI interconnect, is defined by the CTA 861.3 - HDR Static Metadata Extensions, which are discussed in more detail in section B33.9.2.

B33.6.2.2 Dynamic Metadata

It can be beneficial to describe image related metadata with a higher temporal granularity than describing the full content piece (as is the case for static metadata). To differentiate from a temporally global approach, such metadata is commonly referred to as **Dynamic Metadata**. Dynamic metadata can provide auxiliary properties about temporal subdivisions of the content piece. Such information about temporal subdivisions is beneficial as individual HDR properties such as the minimum and maximum luminance or the average signal level can significantly vary over the duration of the content piece. The granularity can be addressed down to a single frame, providing very exact sets of metadata about the pixels and their distribution of the frame. However, a common approach is to vary the metadata only amongst shots or scenes, separated by scene or shot ‘cuts’³⁶. Within a shot, the metadata values are commonly kept constant.

Similar to the SMPTE ST 2086 describing static metadata, the more recent standard ST 2094 “Content-Dependent Metadata for Color Volume Transformation of High Luminance and Wide Color Gamut Images” describes dynamic metadata. This includes ST 2094-10 (Dolby Vision), Color Volume Reconstruction Information (CVRI) SMPTE ST 2094-20 (introduced by Philips) and Color Remapping Information (CRI)³⁷ defined in ST 2094-30 (introduced by Technicolor), and HDR10+ ST 2094-40 (introduced by Samsung).

Figure 15 illustrates the fundamental differences between static and dynamic metadata approaches. In this example content piece, the Static Metadata (a) describes the fundamental statistical properties. Here, the ultimate luminance range is defined by the format or protocol, which for PQ is 0.0 (not depicted) to $10,000 \text{ cd/m}^2$. The mastering display metadata

³⁶ Content pieces such as a movie is made up of large amounts of individual shots that are all placed together during a post-processing step called editing. The simplest case to connect two shots is with a ‘cut’ where the last frame of the preceding shot is instantly followed by the first frame of the next shot. Nevertheless, there are several other transitions possible such as fades, wipes, etc.

³⁷ Not to be confused with Color Rendering Index which is a quantitative measure to identify how faithful a particular light source can reveal the colors of various objects in comparison with a natural light source (CIE S 017/E:2020).



identifies the capabilities of the display used to master (or color grade) the content. This dynamic range is typically less than the maximum facilitated by the protocol and is in this example provided as 0.005 to 4000 cd/m². Any given piece of content does not have to reach to the mastering display's maximum luminance. This information is provided by the MaxCLL metadata parameter and here is reported to be 1000 cd/m². The final parameter is MaxFALL, which provides the average pixel intensity over all pixels.

Again, all this information is assigned for the full duration of the piece of content, independent of the variability of the content pixels over time. This is where dynamic metadata becomes useful. Figure 15(b) illustrates how the statistical properties of each shot of the content changes, for example, high luminance bracket to a lower one. Also, the variation of the average signal level (ASL) is provided. If beneficial, the granularity can be increased to a frame-by-frame level as shown by Fig. 15(c). Here the parameters change can be provided freely and independent from each other.

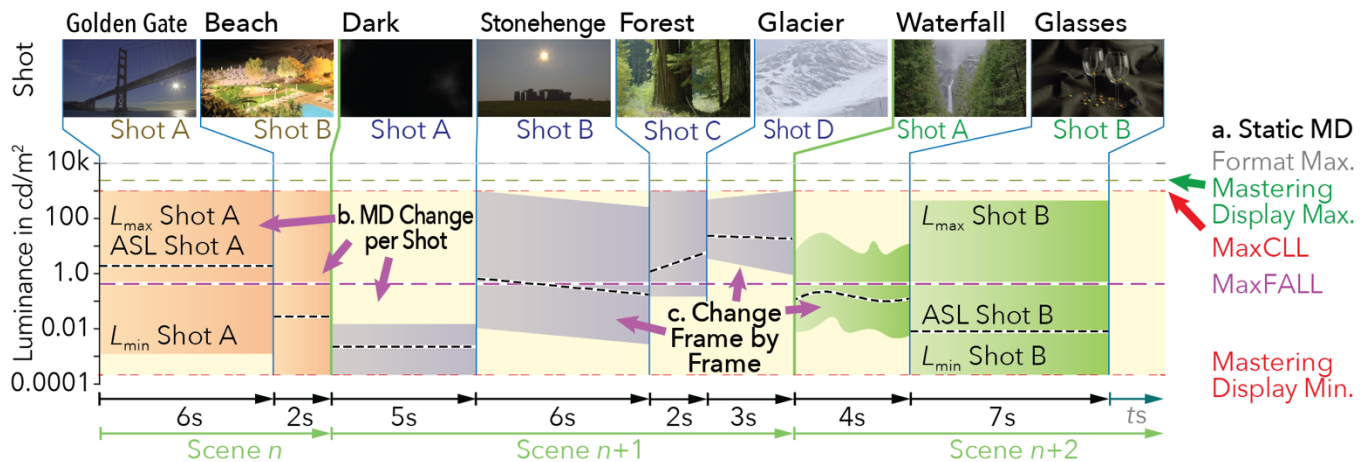


Fig. 15. Concept of static versus dynamic metadata

It is important to point out that image related metadata typically only provides information about fundamental content aspects e.g., of statistical nature. The metadata does not describe or define the final appearance on a target display device³⁸. Nevertheless, in order to optimize the picture appearance for a particular display's capabilities, the image related metadata supports the target display's tone-mapping operator, discussed in the following section.

B33.7 Tone mapping

The previous section introduced and discussed the properties a signal capable of conveying higher dynamic ranges has to exhibit while avoiding visible artifacts such as contouring. Most current HDR displays are not capable of displaying the exact HDR signal as it was originally created. Instead, the rendering capabilities of a display might be lower (but could also be higher) than requested by the HDR signal. Therefore, another important aspect in an HDR imaging pipeline is the need to change the properties of the referred input signal. A typical example is the reduction of the maximum luminance in the case that the target display system is not able to render the peak luminance values described by the input signal. This point also relates to chromatic aspects, for example, if the color gamut needs to be reduced from ITU-R BT.2020/2100 gamut down to ITU-R BT.709 or to other individual display hardware specific primaries.

Such operations can be carried out by tone mappers or tone-mapping operators (TMO) as referred in the computer graphics community. It is beneficial to first define the most important criteria of a tone mapper [Ward 1997]³⁹:

1. The **reproduction of visibility** which identifies if an object is visible on the target display, if and only if it is also visible in the real scene or content. This means that a tone mapper should not create artifacts that were not visible in the source content.
2. Preservation of the **subjective experience**, which means that a tone mapper should maintain the overall impression or intent based on brightness, contrast, and color of the source scene.

³⁸ Some commercial HDR formats offer metadata parameters that do provide information about appearance aspects. See section 0 for more detail.

³⁹ Please note that terms and concepts related to tone value remapping originate in several separate fields such as computer graphics, color engineering, and display engineering. The discussion of the tone-mapping topic in this tutorial intends to strike a balance of term usage amongst those fields.



There are several approaches on how to achieve such adjustment of luminance and chromatic values while following these criteria. One approach is to simply normalize or rescale the input signal to the luminance and chromatic capabilities of the target device. This approach, which is also called **relative colorimetric rendering intent**, does retain all the relative relations amongst pixel intensities and colors, but typically at the expense of a reduction in contrast or saturation of the image. As this approach tends to negatively impact the image appearance and its creative intent, it is not commonly used beyond relatively small dynamic range adjustments.

Another approach is to follow **absolute colorimetric rendering intent**, also commonly referred to as clipping & crushing. With this approach, the input signal is rendered as close to the original as possible while keeping the absolute relations amongst pixels intact. At the point where the requested luminance goes beyond the display's capabilities, the signal is simply cut or 'clipped' to the most extreme value that can be successfully rendered by the display⁴⁰. 'Crushing' is the analog to clipping on the dark side: If the display's black point is higher than the one requested by the signal, the signal is crushed at the lowest possible level. When using an absolute signal such as one based on PQ, the intention is that the clipping and crushing luminances will match the respective luminance thresholds of the actual display device. However, if the display is not calibrated, the signal clipping luminance and the actual measured luminance do not necessarily match.

In order to strike a good balance between detail preservation and contrast loss, the required approach gets more complex and can be referred to as **perceptual rendering intent**. Such approaches are commonly what is referred when talking about 'tone mapping' (even though the two approaches described earlier may also be considered to be tone mapping). A tone-mapping approach redistributes the intensity values of an input signal to fit the requirements of an output system such as an electronic display. This concept is also known as tone reproduction, signal mapping, display rendering, and signal compression. But as discussed in section B33.3 above, the reader is advised that those terms might also have other meanings. Therefore, care should be taken when communicating.

B33.7.1 Perceptual Mapping

Perceptual rendering intents typically employ non-linear mapping functions that gracefully compress the signal to fit into a limited dynamic range. This is colloquially called 'roll-in' or 'roll off', e.g., of highlights. This non-linear mapping can be implemented globally ('**Global Tone Mapper**'), which means that the mapping function is applied uniformly for all image pixels, or as spatial operator ('**Local Tone Mapper**') where the mapping operation is applied both in the intensity and spatial domain.

B33.7.1.1 Global Tone Mapping

Figure 16 illustrates the fundamental concepts of a global tone mapping approach. Example (a) depicts the input signal without mapping. Example (b) illustrates absolute colorimetric mapping or clipping & crushing, and (c) shows perceptual tone mapping.

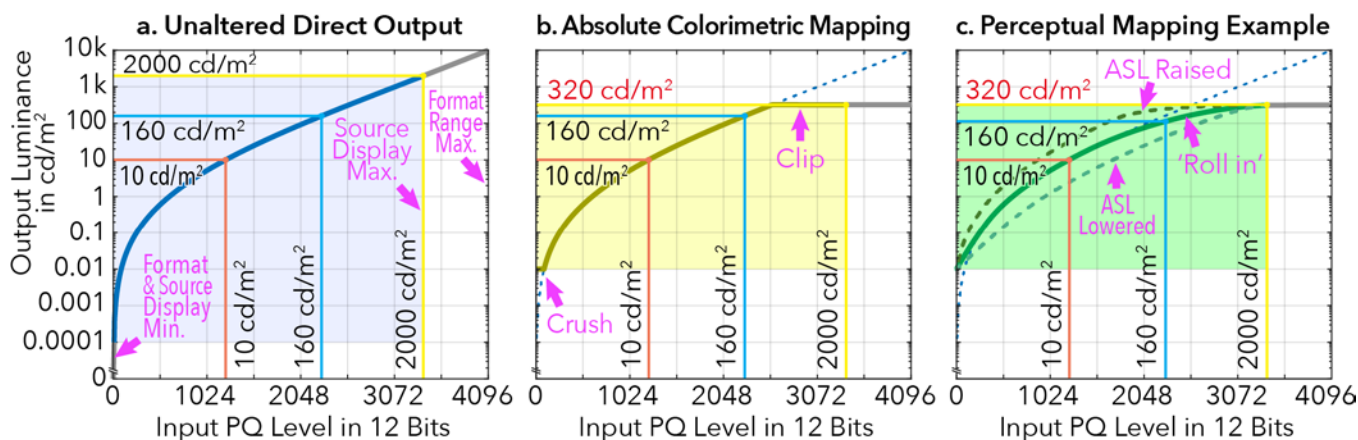


Fig. 16. Luminance value adjustments to reduce the signal dynamic range

The example in Figure 16(a) shows how HDR signal codewords are mapped to absolute luminance values. The x-axis depicts the 12-Bit code range, and the y-axis represents the full luminance range of 0.0 to 10,000 cd/m^2 as specified for the PQ EOTF. The blue rectangular area depicts the capabilities of the source display that is recorded in the signal as well as the directly resulting luminance window. To further support this illustration, three example luminance levels are labelled at

⁴⁰ There are several approaches on how to map colors to the nearest point within the color gamut, but discussing those approaches is out of scope of this tutorial. Please refer to [Morovič 2008] for more detail.



10, 160 and 2000 cd/m^2 . In this example, a display that is capable of covering the exact signal extent could now theoretically⁴¹ display it in its entirety, without requiring tone-mapping.

Figure 16(b) illustrates absolute colorimetric mapping. Here, the horizontal extent of the yellow rectangle again depicts the capabilities of the source display. However, in this example, the target display's capabilities are limited to a luminance range from 0.01 to 320 cd/m^2 . Again, the three source luminance examples of 10, 160 and 2000 cd/m^2 are present. In this absolute colorimetric mapping case, the 10 and 160 cd/m^2 luminance levels are within the target display capabilities and therefore can be rendered exactly as dictated by the source signal. However, because the target display is not able to reach 2000 cd/m^2 , it will clip the maximum luminance of any code value greater than its own maximum luminance of 320 cd/m^2 .

The third example shown in Fig. 16(c) illustrates a basic approach to perceptual mapping. As mentioned earlier, there are many different implementation approaches for perceptual mapping. These can be significantly more complex, especially if dynamic metadata is considered by the tone mapper. In the example, the green rectangle depicts the source and target display's capabilities, which match the extent rectangle of example (b). As the maximum luminance again is limited to 320 cd/m^2 , the 2000 cd/m^2 maximum luminance of the source signal cannot be reproduced by the target display. The peak therefore has to be re-mapped (sometimes colloquially called 'brought in'). But instead of a 'hard' clipping at 320 cd/m^2 as in example (b), the source PQ EOTF is gradually compressed or 'rolled in'. This means that the tone curve starts to deviate from the PQ EOTF around 12-bit PQ level 1800 and continues shallower to intersect at the maximum luminance of both source and target display maximum luminance. The effect of this process is that bright image areas are not simply clipped, which would leave an appearance that can be described as a 'plateau', but instead still honors and reproduces the textures and detail of the bright area to some extent. Nevertheless, the lower the target display maximum luminance, and with that greater the difference between source and target maximum luminance, the more the highlight detail is sacrificed in order to maintain the general appearance and contextual cohesiveness of the overall image. Adhering to the EOTF as close as possible throughout the luminance range is one option. However, it is also possible to adjust and map the output (y-axis of Fig. 16(c)) generally higher or lower. This approach has the effect of changing the general appearance of the content. Mapped higher, the average signal level is raised, making the image overall appearance brighter (this is commonly used by high ambient viewing modes as described in section B33.9.3.1). However, this method comes at the cost of highlights that are compressed even more, potentially losing more detail than in the previous example that tracks the EOTF in the darker and mid-value range. It is also common to lower the ASL, especially with displays that are offering good black levels and are viewed in dark environments. In this scenario, highlights can potentially be less compressed, and more detail might be retained.

Figure 17 illustrates the three examples given by of Fig. 16 based on an actual image. The source image given by Fig. 17(a) reflects the source signal with the full 2000 cd/m^2 maximum luminance as shown by the native response curve of Fig. 16(a). The scanline plot supports this as only the sun disc pixel area is clipped. Note that the photos in Fig. 17 are linearly mapped and the source mid-tones appear darker in order to maintain luminance correlation. If a colorimetric tone mapper is applied, the majority of the tone values remain intact as shown in Fig. 17(b). However, the values beyond the

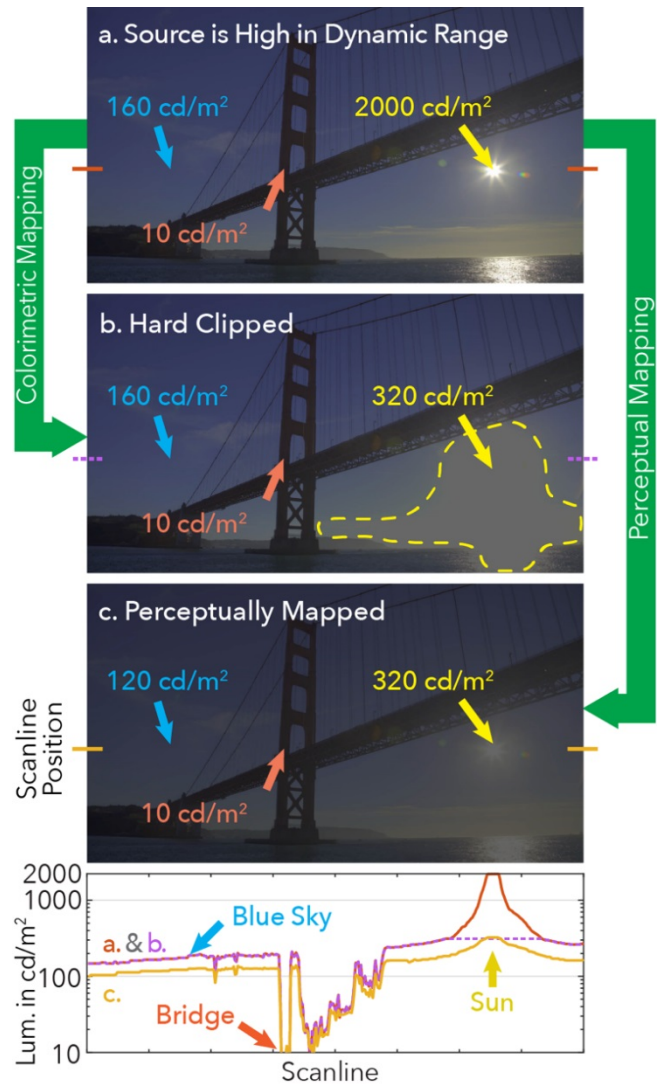


Fig. 17. Differences among source HDR image (a), hard clipping highlights resulting in detail loss (b), tone mapping to preserve the highlight detail (c). The horizontal scanline position is indicated on each photo. Note that the photos in this illustration are linearly mapped and the source mid-tones appear darker in order to maintain luminance correlation.

⁴¹ In reality, there are additional processes in a physical display device that can affect the displayed image even if signal and display offer the same minimum and maximum luminance. This point will be further elaborated in section B33.8 below.



target limit of 320 cd/m² are clipped. In this example, the key area is rather large, about one sixth of the image (indicated by the yellow dashed line). Again, looking at the scanline plot, the clipped or ‘plateaued’ pixel area becomes apparent. Image (c) gives an example of how a perceptual mapper would change the image pixels. In this example, the brighter pixels are affected by the ‘roll in’ in order to provide sufficient headroom to render the sun, even though the gradient slope is shallower than in the source image.

B33.7.1.2 Local tone mapping

So far, the discussed tone mapping approaches have all been global in nature, meaning, all pixels are affected by the same global adjustment rule. The dynamic range compression that can be achieved by a global mapper has been shown to be very effective for the majority of scenarios with electronic information display. However, there can be scenarios where spatial properties in an image or scene have to be taken into account when mapping. This is the case, for example, when the contrast difference between the source and target display is very large. With a local tone mapper, it is possible to compress the lower spatial frequencies of an image while mostly retaining the local contrast of high spatial frequency areas such as texture⁴².

Figure 18 compares the effects of a global (a) and a local (b) tone-mapping operator based on an image of the incandescent light source of a desk lamp. The global TMO (a) maintains the cohesiveness of the image but at the same time loses some high spatial frequency components such as the filament of the halogen bulb.

This is not the case with the image tone-mapped by the local TMO (b). Here, all the detail of the source image is preserved, including the filament of the incandescent bulb. Also, the texture of the metal reflector behind the bulb is accentuated. However, as much as none of the pixels are clipping, extensive use of local tone mapping can severely alter the image appearance and in the worst case destroy the cohesiveness of image areas. For example, as much as the light bulb’s filament can be reproduced at the target display capability, it is uncommon for a viewer to perceive this in the real world. This gives the image rendition an unrealistic appearance. Another artifact that can materialize when using local tone-mappers is the appearance of halos at high-contrast edges.

Another aspect to consider, even though not immediately related to display metrology, is the fact that local tone-mapping is computationally more expensive, requiring, for example, a full image frame buffer when mapping instead of pixel or line buffers for global mapping.

Fundamentally, both approaches have their benefits and disadvantages. They can also be used in conjunction with each other while the individual intensities can be adjusted with a high level of granularity (e.g. the spatial filter frequency). Global approaches are more common today, but local approaches have begun to find application in high dynamic range imaging pipelines as well⁴³.

B33.7.2 Content vs. Container Mapping

Section B33.6 described the difference between static and dynamic metadata. Such metadata is not useful on its own. The metadata can only help increase image fidelity in conjunction with a processing module that can interpret the metadata and facilitate a meaningful image adjustment. Such a processing module typically includes a tone-mapping stage.

The availability of dynamic metadata offers significantly improved mapping options with much higher temporal granularity compared to static metadata or the worst case of no metadata. With a static approach, the temporally global mapping properties for the TMO are set once for the whole content piece and then mapped accordingly independent of any pixels in a given scene actually spanning the whole range of the container (thus called **Container Mapping**). This container can either be defined by static metadata or, if the latter is not available, by the full extent of the signal space itself (e.g., a luminance range of 0 to 10,000 cd/m²). The dynamic approach instead maps each scene or shot individually, based on its pixel properties and can therefore be called **Content Mapping**.

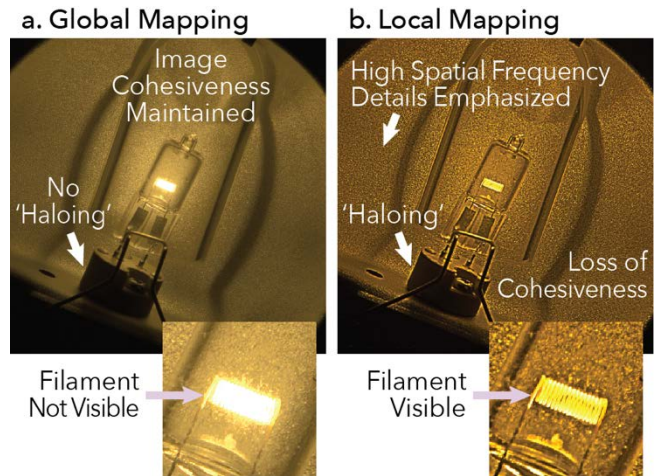


Fig. 18. Global (a) vs. local (b) tone-mapping approaches.

⁴² Over the past 20 years, a plethora of local tone mapping approaches have been published. As before, a good starting point to investigate this topic further is [Reinhard 2010].

⁴³ Please note that tone mapping is often of local nature in the case in other fields such as postproduction or computer graphics. Please refer to [Reinhard 2010] for more information on those application fields.



To elaborate on these two approaches, Fig. 19 shows three different HDR scenes and how they are tone-mapped from source to target display. The left side of the first column shows the source HDR Mastering Display color volume with its associated image pixel point cloud. On the right side of the first column, the color volume and scene pixels distribution of the target display are shown after container or content mapping has been applied. The image examples reflect the appearance after global container mapping (center) and after content mapping using dynamic metadata. For a higher dynamic range source image (a), the appearance of the image using a container mapped approach widely matches that of the content mapped image. This is due to the image pixels reaching almost over the full range of the container. This changes with a High Key Scene⁴⁴ (b) which only occupies the brighter pixels levels of the container but is otherwise not very high in dynamic range. If the image is content mapped using dynamic metadata, the image exposure is lowered and with that, the appearance is maintained on the target display. On the other hand, when using a container mapping approach, the TMO is not aware that the glacier image has a significant ‘foot’ room without any deep black pixel values. The TMO would therefore reserve foot-room for the non-existing code values and lose overall contrast. Similarly, if mapping a dark image, the container-based mapper retains headroom that is not utilized by this particular scene.

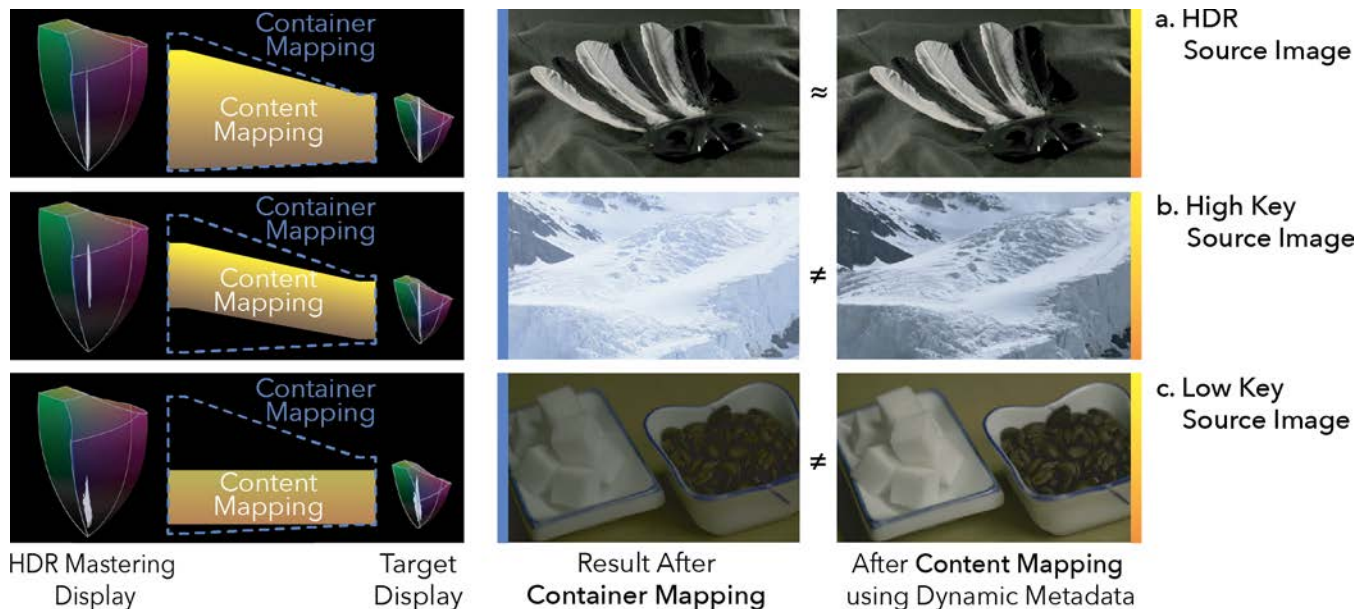


Fig. 19 Example of container vs. content tone-mapping

In real content, the kinds of scenes shown in **Fig. 19(a-c)** will appear in succession throughout the content piece. These examples underscore the benefit of mappings based on dynamic metadata.

B33.7.3 Inverse Tone Mapping

The most common tone-mapping approaches reduce the higher dynamic range of a source image down to the lower range of a target device such as a display. However, there are also applications where it is desired to extend the contrast of a low dynamic range source to a larger luminance range. This is the case, for example, with low dynamic range SDR content that could potentially be displayed with an overall higher dynamic range on a modern display. Even though dynamic range extension can be described by the term ‘tone mapping’, it is more common to use the term ‘inverse tone mapping’ to describe this process.

The simplest inverse tone-mapping approach is to linearly expand the input signal range. This mapping does not necessarily have to reach the limits of the target display. The tone range is extended when the output light spans a higher dynamic range than the content creator intended. Similar to the gentle linear dynamic range reduction described earlier, a gentle expansion can be perceptually acceptable. However, if the ‘stretch’ extends the source to a significantly larger luminance range, then image cohesiveness can suffer. Continuing the conceptual illustration approach described in Fig. 20: Figure 20(a) shows the PQ curve. Images (b) and (c) depict examples of inverse tone-mapping approaches. The source image is limited to a dynamic range from 0.1 to 320 cd/m² as depicted in image (d). In image (e), signal normalization of the image

⁴⁴ High key scenes are comprised of mainly light tones. In the context of HDR, one can also assume that high key scenes cover a higher luminance range bracket. Low key scenes describe the opposite where the scene is mostly comprised of dark tones at lower luminance levels. This does not necessarily mean that high or low-key scenes exhibit clipped or crushed pixel values.



extends the output dynamic range from 0.001 to 2000 cd/m^2 when using the mapping curve provided by (c). Note that not only is the already blown out sun-area significantly amplified, so also are the sky and the bridge⁴⁵.

Again, a solution could be to perceptually map the source to target in a non-linear fashion. However, there are several challenges: While it is possible to derive a mapping curve that amplifies the bright and highlight regions of an image only, the challenge lies in the fact that a typical SDR image does often not include highlight details that could be amplified. Instead, SDR images often exhibit clipped or featureless areas caused by in-camera clipping of the light source when capturing the scene⁴⁶ or when color grading to an SDR deliverable.

Several inverse-tone-mapping approaches have been proposed in the scientific literature and also are implemented in current displays such as consumer TVs. Their complexity ranges from simple approaches given by the example in Fig. 20 to more involved local expansion approaches or even deep-learning based highlight reconstruction approaches. ITU-R BT.2446-0 as well as [Reinhard 2010] cover different approaches for tone mapping and Inverse Tone mapping in detail.

B33.7.4 Gamut Mapping

Many tone-mapping approaches consider processing of color images. However, often, they emphasize the accurate mapping of achromatic information in an image and re-assign color after the mapping step. This can be but does not always have to be colorimetrically or perceptually accurate. If color mapping is of particular significance, the signal mapping approach can also be referred to as ‘**Gamut Mapping**’. The term gamut mapping originates from the color engineering field and has already found countless applications outside of HDR imaging. These include the concepts of relative and absolute colorimetric as well as perceptual rendering intents introduced earlier. A relatively new concept to combine the emphasis on both intensity and color gamut re-mapping is described by the term ‘**Color Volume Mapping**’. A discussion of gamut and color volume mapping is beyond the scope of this tutorial and more information can be found in [Morović 2008].

Ultimately, the name and scope of a particular mapping approach is flexible. The reader is advised to assess a particular mapping approach in the context of a metrological assessment. For completeness, it is also important to mention another process that serves a similar purpose as the tone-manipulation approaches described above, which is the manual re-mapping of a source image by an artist such as as colorist or photographer.

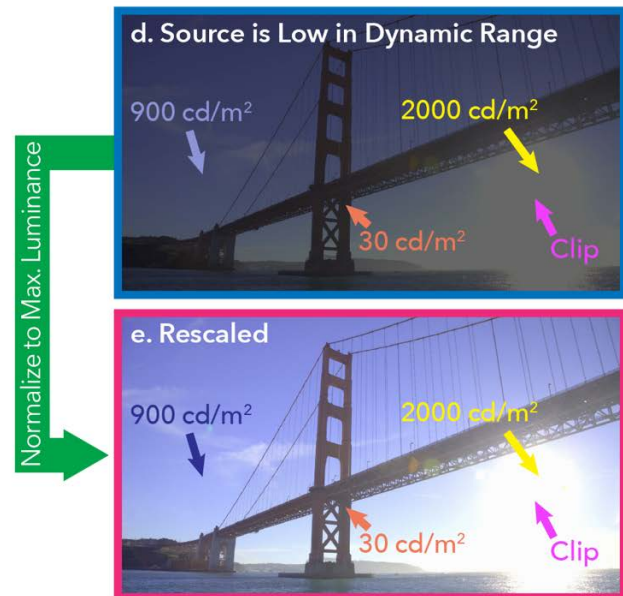
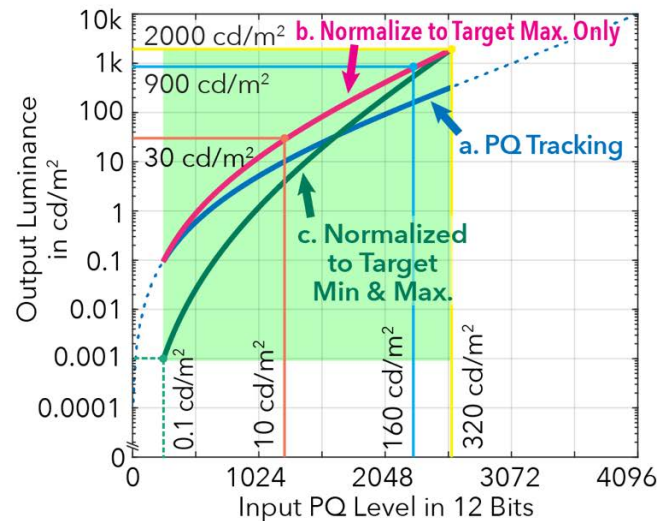


Fig. 20. Examples of fundamental global inverse tone-mapping approaches.

B33.8 Display Device Properties

The previous sections elaborated the requirements for an image signal that can facilitate content with extended dynamic range as well as wider color gamuts. As the fundamental capabilities of displays to physically render minimum and maximum luminance levels as well as color gamut requirements can vary greatly, the concept of tone mapping was also discussed. The latter typically maps the source signal properties to a single, *static* description of the target display properties. However, as indicated in section B33.4, modern image displays are typically not static in their response to a signal. This means that

⁴⁵ As before, the image examples are linearly mapped, therefore, even though the rescaled example (e) might look acceptable in this illustration, when viewed on a modern display, several areas would be glaringly and unnaturally bright.

⁴⁶ This is more of a problem with video cameras as chemical film (for example) did not harshly clip highlights. Also, modern digital cinema cameras have significantly more latitude and better approaches to mitigate highlight clipping.



depending on the spatial or temporal properties of the incoming signal, the light output of an individual pixel can vary, even if its signal value remains constant.

One reason for this behavior is that modern display systems have successively added comprehensive adaptive behavior such as spatial and temporal power adjustments, subpixel color and geometry algorithms, dual-modulation algorithms, and others. This is not to say that ‘traditional’ displays were free of dynamic behavior: There have always been impacts from manufacturing variability, aging, and thermal issues. However, measurable variability has increased substantially with modern displays.

To address those aspects of the imaging pipeline, the properties and behavior of the display hardware have to be discussed. This includes the fundamental image generation technology, a display’s control system that actively influences the display behavior in order to manage power consumption, thermal issues, and any other adaptive behavior. Again, as mentioned in section B33.4, it is important to point out that this adaptive behavior is not necessarily dependent on the presence of an HDR input signal⁴⁷. It is more a property of the actual display design, which became beneficial in order to reach the rendering requirements of HDR content. Nevertheless, a display’s SDR modes can also utilize and benefit from the adaptive behavior of modern display systems, even though this might often be to a lesser degree⁴⁸.

Assessing all those properties in a meaningful manner poses one of the biggest challenges to thorough display metrology and therefore deserves particular attention of a metrologist. Unfortunately, the intrinsic configuration of display hardware features as well as functionality of many of the display’s control systems are usually not public knowledge and therefore have to be treated as a ‘black box’. Nevertheless, many fundamental concepts of the display technologies used with modern information displays are well known and described in the literature [e.g., Hainich 2017, Reinhard 2010, Seetzen 2004, Tsujimura 2017]. Another point is that a display’s tone mapping can be intertwined with the display’s control system. This further complicates assessment and therefore if at all possible, it is recommended to disable tone mapping processes when assessing a display.

The challenges and pitfalls regarding performance and behavior of current and near-future display systems can be divided into **accepted/known shortcomings** and **coincidental shortcomings** [Kunkel 2016b]: The accepted/known shortcomings include economic decisions (cost of device, energy budget, and – with dual modulation displays – the number of backlight zones, type of panel, and dual modulation algorithm). Also, there are historical implications such as the reuse of legacy chipset blocks and backwards compatibility. Coincidental shortcomings can be facilitated by the complex behavior of advanced technologies such as dual modulation, power delivery to the actual pixels, and other forms of energy budgeting, which make display assessment more complex. In either case, some behaviors are inherent to the properties of the physical display while others might be based on rules set by software. While the former likely cannot be altered throughout the lifespan of the display, the latter properties can potentially be manipulated throughout device firmware updates and calibration.

In reality, a display is designed with a certain defined performance envelope, based e.g., on feature requirements or a targeted price point. Ideally, any copy of the same display model should perform the same. However, there can be some level of variability amongst units of the same model due to **manufacturing variability**. Those variabilities can be caused by the tolerances of the utilized hardware components (e.g., variations between panels, level of LED binning, and so on).

The following sections describe behavior that can be observed with modern displays and that might ultimately make the light output of the display device differ from the received signal and tone mapping targets. Please note again that this section provides fundamental information that is valuable to a metrologist. It does not refer to any specific product. Further, some of these effects might have been alleviated or resolved in the latest display devices. Nevertheless, as a metrologist might encounter these effects when dealing with current or legacy devices, it is beneficial to discuss them.

B33.8.1 Spatial Variability

Figure 22 illustrates various display stacks. A basic LCD system (a) uses a backlight unit (BLU) with illumination elements at the edge(s) of the display and optical light guides to distribute the illumination evenly behind the LCD panel. High local contrast levels are required for rendering of HDR imagery. To meet this need, one fundamental technology that enabled significant progress is **Full Array Local Dimming (FALD)** for LCD-based systems. Another term for this concept is **Dual Modulation** as the interplay between the backlight’s LEDs and LCD pixels is not necessarily just for dimming. In FALD (b, c), an array of LEDs is directly placed behind the panel. Each of those LEDs can be modulated individually, locally increasing or decreasing the luminance of the LCD pixels in front of the LED, thereby increasing the overall luminance range of the display system. In some implementations, modulation optimization processes [e.g., Seetzen 2004, Reinhard 2010] can

⁴⁷ Dynamic Metadata might influence the display’s adaptive behavior.

⁴⁸ There might be SDR picture modes that still drive a display to a performance envelope that would be typical for displaying HDR content. Examples include so called ‘Vivid’ (see section B33.9.3.1) or inverse HDR ‘stretching’ modes (see section B33.7.3).



be used in order to compensate for the point spread function (PSF)⁴⁹ of the LEDs. Control of individual LEDs can significantly improve the local rendering capabilities of the display compared to a globally-controlled backlight. Capability of the display system depends on, among other things, the number of individual LEDs that are part of the FALD array. Small, high contrast features can generally be rendered more accurately with a finer array containing more backlight elements (c). This ability is sometimes referred to as ‘**HDR small feature rendering capability**’. Mini-LED backlights fall into this category (c). Self-emissive display technologies, such as OLED or LED displays, do not rely on an additional light source as the individual pixels emit their own light (d). Therefore, self-emissive displays do not fundamentally have any spatial limitation other than the actual pixel-related resolution. Another system approach is to use two liquid crystal light modulators, sometimes called a dual-LCD structure (e). When used in combination with a static or modulated backlight, dual or triple modulation (respectively) is possible. If the two LCDs have the same spatial resolution, there is also no spatial limitation caused by the light source modulator⁵⁰.

The reader is advised that there are cost and performance tradeoffs across all of these approaches, and one approach is not necessarily superior to another. The fundamental effectiveness of the dual modulation approach has been thoroughly studied [e.g., Seetzen 2004], and it has been shown that very high contrast, although important on a global scale, can in most cases not be perceived by humans at high spatial frequencies⁵¹. Ultimately, a display’s picture quality is dependent on several factors and cannot be determined by the light modulation technology alone.

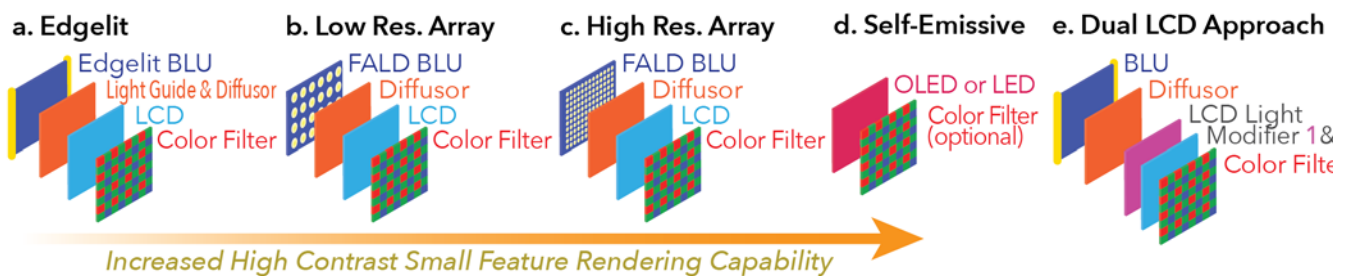


Fig. 21 Display stacks with common spatial light modulation approaches. The order of the elements might change depending on the level of implementation of the technology.

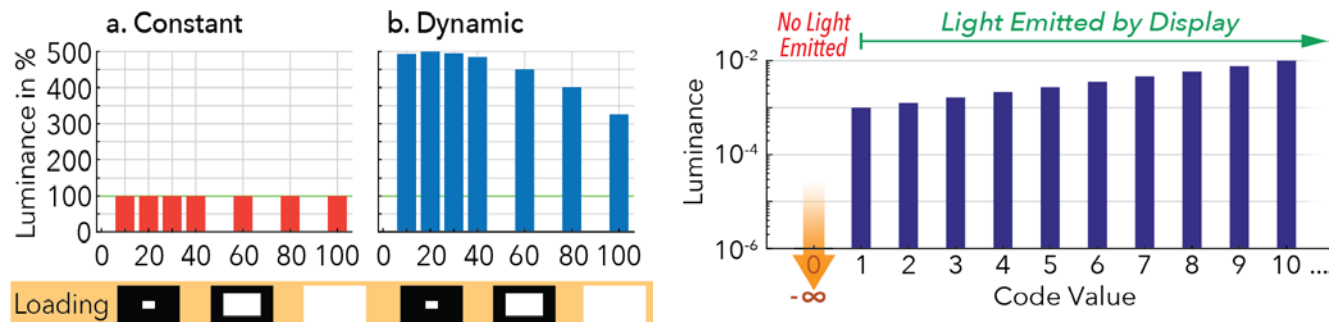


Fig. 22. Issue with many modern displays: luminance roll-off for high APL.

Fig. 23. The concept of ‘Fat Zero’. The codewords follow an EOTF and quantization granularity that prevents appearance of contouring. However, at the lowest codeword (in this example 0) a pixel is switched off, leading to a deep black. This causes a large luminance change between code value 0 and 1 which can be perceived as an artifact.

Almost all modern display technologies, including LCD, OLED, and LED approaches, are still bound to power consumption limits and therefore, larger **loading targets** (see ICDM Section A12.2, ICDM test pattern tp-HL01) will also often result in lower maximum luminance levels. This point is illustrated in Fig. 22: Fig. 22(a) illustrates the loading behavior of a legacy, global, non-modulated backlight. The display’s luminance is constant regardless of the displayed content. Figure 22(b) illustrates many modern displays with adaptive behavior. When displaying loading targets that occupy

⁴⁹ There are several approaches toward spatial light distribution from direct LED backlights and not all of them are based on continuous PSFs. Examples include backlight blocks or complex reflector pattern that influence the LED’s PSF. Please refer to the cited literature for more detail.

⁵⁰ It is possible to design dual LCD systems where one LCD has a lower spatial resolution than the other.

⁵¹ There are extreme examples such as a starfield composed of many objects in a scene that are both small and bright on a black background.



larger parts of the display area, up to 100% average picture level (APL), the maximum luminance can and often does drop. In this case, a full-screen maximum signal value (APL=100%, or ‘full screen white’, also known as L100 and “FW”) can be displayed with a significantly lower luminance level than a loading target with a lower value (e.g., 20% to 40% APL, i.e., L20 or L40)⁵². Nevertheless, due to technological progress, the luminance levels of modern displays are higher over the entire APL range, even with a 100% APL target, compared to legacy displays with unmodulated backlights.

Note also that there are options that are referred to as pixel dimming which do not necessarily involve a second light modulator such as a FALD backlight. Even though those approaches can offer effects that can appear similar to those observed with dual modulation techniques, they are dependent on the contrast of the single modulation device such as the LCD panel and are more in the domain of a local tone mapper (see section B33.7).

Another effect that can be observed with some display device technologies is a large tone curve discontinuity at the low end of the tone scale. Even though the codewords follow an EOTF and quantization granularity to prevent the appearance of contouring, the lowest code word exhibits an EOTF discontinuity with a ‘jump’ out of black. This means that pixels with the lowest code word are physically switched off and with that are not actively creating light⁵³. However, adjacent pixels, even with the next lowest code word, are rendered with a significantly higher luminance level. This concept is colloquially referred to as ‘Fat Zero’ and is illustrated in Fig. 23.

B33.8.2 Temporal Variability

Another dimension to consider is temporal variability. This relates to all processes where the displayed image content changes over time, independent of the received signal. One of the most common temporal behaviors is the dimming of bright pixels or the whole screen after a given time, while the image content provided by the signal remains static (e.g., when displaying a photo or a static full-screen GUI). In some cases, this can also include minor motion where only a small percentage of pixels change over time. This display behavior is beneficial to prevent potential image retention (see IDMS Chapter 10 for more information), for thermal management, or to preserve power.

Another effect that can be observed with some modern display systems is a delayed or complex luminance rise behavior. This means that, for example, after a duration of content with a lower average signal levels, the ASL suddenly rises and with that ‘requests’ high luminance output from one or more pixel areas on the display device. The optical reproduction of the higher luminance as requested by the now higher ASL might not be instantaneous and may require a certain number of frames or refresh cycles to be reached. Similarly, the displayed luminance levels might be reduced again after a given time e.g., to protect the display system from excessive thermal build up. The latter is not necessarily related to the dimming behavior when static content is detected and can happen with any content that requests prolonged high average picture levels.

B33.8.3 Spectral Variability and Multi-Chromatic Displays

The Spectral Power Distributions (SPD) of the display primaries and white point have an impact on the display’s color rendering capabilities. At first glance, this might not appear to be related to HDR imaging⁵⁴. However, the spectral properties of the display device have a significant impact on how high dynamic range imagery can be rendered. Also, as the fundamental display technologies have diversified as discussed above, so have the spectral responses amongst the technologies.

Fundamentally, an SPD describes the energy levels of a light source through a range of wavelengths of light⁵⁵. Therefore, one common analogy is that the spectral power distribution is the true “fingerprint” of a light source. The spectral response of a color primary can be approximated by the peak location and the curve’s spectral width. Traditional display imaging technologies such as CRT, CCFL, and single phosphor white LED backlight units exhibit **broader spectral width primaries** which in turn result in smaller possible color gamuts. **Narrow** (or colloquially called ‘**sharper**’) **primaries** e.g., exhibited by dual-phosphor LED, RGB LED, OLED, quantum dots, and laser light sources have the advantage of wider color

⁵² The number associated with the loading pattern (e.g., ‘L20’) refers to the diagonal of the pattern in respect to the display diagonal. Additionally, loading pattern are also commonly defined as relative display area. The conversion from area to diagonal of a pattern P can be carried out with the following equation: $P_{Diagonal} = \sqrt{P_{Area}} \cdot 100$. For example, a 10% area relates to an L32 loading pattern.

⁵³ From a metrology point of view, those pixels are not completely void of photon emissions as there will likely be lateral scattering in the display panel material, raising the black level to some degree.

⁵⁴ This is not limited to HDR signals and is also relevant when displaying other signal types such as SDR on modern displays. More information is provided in IDMS chapter 23.

⁵⁵ The spectral band of visible light is limited to the wavelength range of 380 to 780 nm. This band is covered by the photometric measure of luminance (see section B33.5.1). Nevertheless, as light is part of the electromagnetic (EM) spectrum, an SPD is fundamentally not limited in wavelength. The EM spectrum is referred to by the measure of radiance.



gamuts. Figure 24 illustrates the spectral power distribution (SPD) of three display illumination types. In this image, (a) illustrates the SPD of a typical white LED backlight which is based on blue LEDs with embedded yellow phosphor (the ‘notch’ at 580nm is caused by the LCD’s color filters). The CCFL SPD (b) is complex due to its chemical properties but is nevertheless a spectrally broad light source. The laser light source (c) is spectrally narrow due to the monochromatic nature of laser light.

It is important to point out that when the peak wavelengths and sharper energy distributions are weighted to a tristimulus representation, those tristimulus values do not always match the values defined by industry standards such as DCI-P3 or ITU-R BT.2020. This can complicate calibration and potentially reduce the available color gamut area. Another problem with sharper primaries is an increased risk of metameric effects which is a negligible issue with broader light sources.

There are two sources of metamerism mismatch: Between instrument and observer, and between observers. The **instrument-observer metamerism** is strongest for tristimulus measurement devices when measuring displays with narrow primaries. This can be mitigated by using spectral measurements e.g., with a spectroradiometer, or by calibrating a tristimulus measurement device with spectral measurements for each specific type of display technology (refer to IDMS section B1.2). The **observer-observer** (or **inter-observer**) **metamerism** is the reason that different observers looking at the same display may perceive different colors. The root cause is that the commonly used CIE 1932 2° Color Matching Functions (CMF) do not account for differences between observers, and according to recent studies do not represent the average of viewers either [Sarkar 2010, Asano 2020]. To counteract the average observer problem, a ‘Judd-Vos offset’ [Vos 1978] is sometimes used to improve color matching between two display types (typically CRT and LED or OLED). But the usual method of ‘correcting’ for this only involves adjusting the white point. The primaries, and all other colors, are still related according to the CIE 1931 CMFs. Even though attempts have been made in putting forward alternate CMFs that improve over the Judd-Vos offset techniques, there are still problems where the difference between individual observers can exceed the difference between alternate CMFs. Therefore, even if the color match is improved for a single observer, the color matching may be made worse for another.

Another approach toward extending the capabilities of a modern display device is to use more than three fundamental physical light sources or colorants (each with their own SPD). Such **multi-chromatic displays** add another color to the typical red, green, and blue primaries, for example, white, another green, cyan, or yellow sources. With this approach, such displays can extend some portions of the color volume. For example, due to the high power to luminance ratio, adding a white sub-pixel enables a display to reach higher maximum luminance levels required for high dynamic range imaging. On the other hand, such approaches further complicate the calculation of the expected values from a display as they no longer operate in a simple additive manner. It is also possible that multi-chromatic configurations may actually limit or reduce certain portions of the color volume envelope.

From a metrology point of view, because simple assessments such as checking for additivity do not provide sufficient information, more advanced models that are able to model the spectral and multi-chromatic behavior of modern displays are required in order to quantitatively evaluate their performance. The reader is referred to IDMS section 5.32.

B33.8.4 SDR vs HDR Accuracy

The SDR mode, with its lower dynamic range and gamut definitions, is usually not challenging the capabilities of current HDR displays. For example, content that follows ITU BT.709 and BT.1886 with 0.1 to 100 cd/m² will only use a subset of the typical rendering capability of a modern display, as the modern display often reaches significantly deeper blacks, higher luminance levels, and a DCI-P3 or wider color gamut. Therefore, there is a significant amount of headroom and foot room towards the hardware limits of the modern display device. Such a display is likely less challenged by the content and achieving acceptable measurement and accurate calibration results to the standard might be straightforward or at least easier to achieve.

However, the situation is different for HDR mode. The signal usually arrives in the display system requesting a significantly higher dynamic range beyond the display’s rendering capability. This mismatch is remedied by using a tone mapper. However, in order to provide the best possible viewing experience, the tone mapper is attempting to use the capabilities of the display to the maximum extent. Accordingly, the display can be driven at its specified hardware limits, which might have an impact on stability and measurement accuracy.

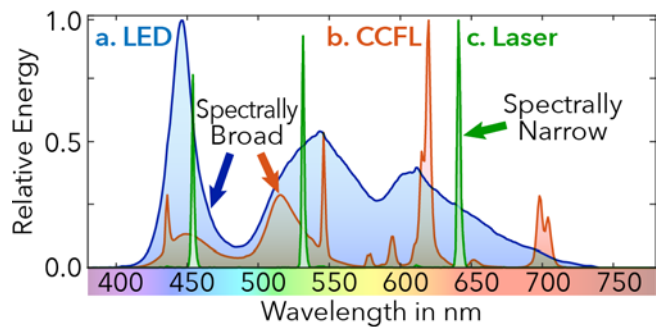


Fig. 24. Spectral power distribution (SPD) of three display illumination types: LED (a) and CCFL (b) backlights are spectrally broad, leading to a reduced color gamut; a laser-based illumination source (c) is spectrally narrow or ‘sharp’.



B33.9 Application and Deployment

Now that the fundamental HDR signal and display particulars have been discussed, it is important to identify how HDR content can be facilitated, from content creation via deployment and to the place of consumption. To provide a high-level overview, Fig. 25 outlines the most common components and aspects that are most important to display metrology. Other components of the imaging pipeline are out of scope and therefore are not discussed. The relevant components can be separated into three main segments: Content creation (a), delivery to consumer (b), and consumer display (c). Even though there is some overlap amongst them, each of those segments typically has to deal with its own particular approaches, opportunities and challenges of how HDR technologies are utilized.

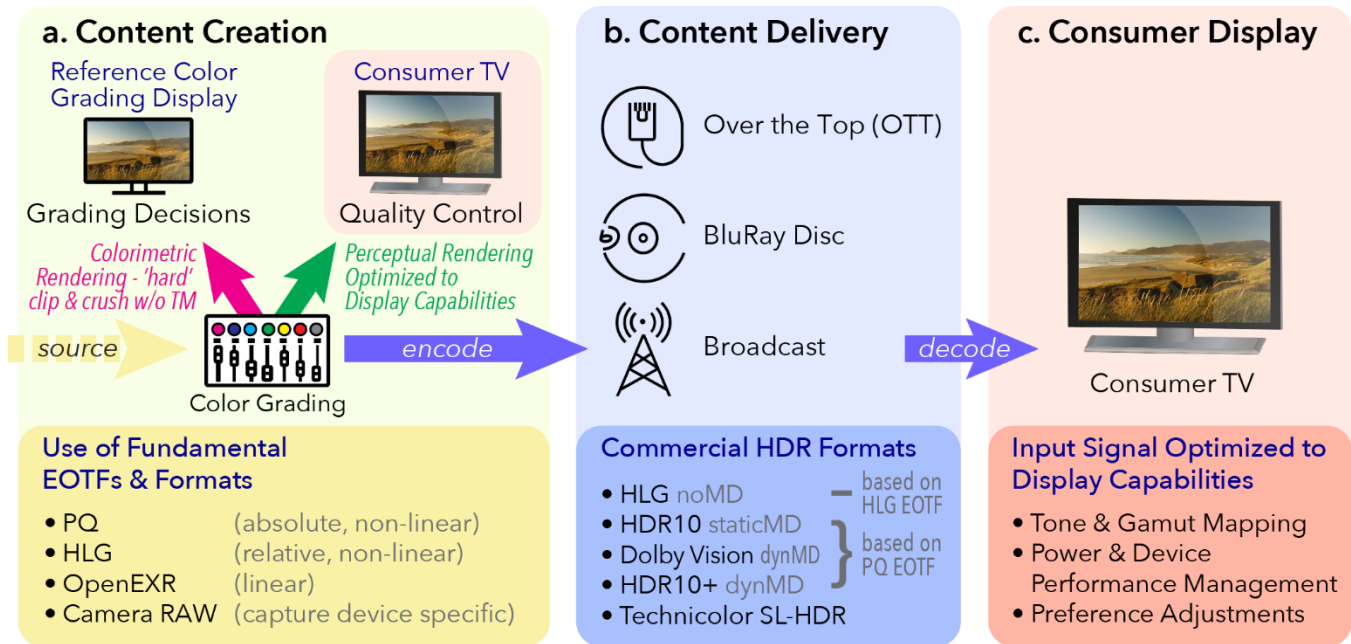


Fig. 25. The three fundamental imaging pipeline segments relevant to display metrology: Content creation (a), content delivery (b), and consumer display (c).

One fundamental observation is that each component in the depicted pipeline can affect the signal and ultimately the rendering and picture quality a viewer is able to experience. Therefore, care has to be taken, by both users handling and processing HDR signals (such as engineers, technicians, creatives and researchers), as well as the set-up, configuration, and calibration of hardware and software products that facilitate HDR signals. The ultimate goal is to assure that the content is presented as intended to the visual system. In the following, the three components of Fig. 25 are discussed in detail.

B33.9.1 Content Creation

In order to create meaningful image or movie content that follows creative decisions or other appearance guidelines, adjustments to the image or video signal have to be applied. This could be carried out by a colorist, director of photography or director in a typical movie production setting. In a broadcast production it could be the camera operator and shader. Furthermore, this process can also be carried out by independent content producers creating content, e.g., for online video sharing platforms.

After ingesting content, e.g., from editing, post processing, etc. (depicted as 'source' in Fig. 25(a) into an editing or color grading system, decisions about the appearance or the 'look' of content are typically made by viewing, judging, and adjusting the appearance of the content on a reference display. Through these steps, the content's appearance is assigned a **creative intent**. By way of this step, the signal also becomes display referred as now, each pixel of the content piece's signal has received intent based on their appearance when rendered on the reference display.

The reference display is typically a device that can render the content to be graded in a colorimetrically correct manner, which means that the display follows the EOTF to the extent of its capabilities and clips or crushes the signal beyond those limits. This way, a colorist can assess the appearance of the content inside the reference display, without having processes that adjust the appearance such as a tone-mapper affecting the image rendered on the display. As the creative is approving the intent of a content piece based on how the reference display renders the content, it should be obvious that it is crucial at this point of content appearance adjustment that the devices accurately interact (e.g., software, operating system, GPU, interconnect, display), and that all elements are well calibrated.



In addition to a reference display that is intended to provide colorimetrically correct tracking of the EOTF, often a consumer grade display is used for quality control purposes. This enables the colorist to preview the appearance after tone mapping is factored in, making the rendition on the display perceptual and, if everything is set up and calibrated correctly, correctly preserving the intent. Further information about display requirements as well as the viewing conditions recommended for color grading can, for example, be found in EBU Tech 3320 v4.1 ('User Requirements for Video Monitors in Television Production').

Typical EOTFs used when ingesting content are camera RAW as well as camera or manufacturer related non-linearities with proprietary container and compression formats. Another option is to ingest content using linear light encoding such as OpenEXR. The latter is common with content from special effects departments or software. The output to the reference display typically uses HDR EOTFs such as PQ or HLG as well as a meaningful color gamut that does not limit the content display. It is important to note that here, consumer HDR formats and protocols are not required as the settings of those parameters are under control of the colorist. Only for the preview display, a valid consumer format stream is generated in order to experience how the content will appear on a consumer level display.

B33.9.2 Content Delivery

After the content intent and appearance is approved, it is prepared for delivery as illustrated in Fig. 25(b). This includes the encoding and packaging of the signal into a suitable signal container, with appropriate EOTF and color gamut as well as metadata, if applicable. Please refer to ITU-R Report BT.2390-8 ('High dynamic range television for production and international programme exchange') and ITU-R Report BT.2408-3 ('Guidance for operational practices in HDR television production') for more detail on content production and signal encoding recommendations. Please also refer to section B33.6 regarding metadata concepts.

B33.9.2.1 HDR Capable Formats and Protocols

Commercial delivery paths typically use HDR formats and protocols such as HLG, HDR10, HDR10+, Dolby Vision, or Technicolor SL HDR. Please note that the ICDM is not endorsing any particular format or protocol. These formats are listed below for educational purposes within the scope of this tutorial.

B33.9.2.1.1 The Hybrid Log Gamma (HLG) Format

As discussed in section B33.5.3, Hybrid Log Gamma or HLG refers to a relative EOTF that is composed of a logarithmic and a gamma part. However, the name HLG is also used to refer to the content distribution format that uses the HLG EOTF. The fundamental properties of the EOTF are described in ARIB STD-B67 as well as ITU R BT.2100 (again, see section B33.5.3). The HLG format is designed with the ability to encode wider dynamic ranges while maintaining a level of backwards compatibility to SDR equipment such as displays. It does not utilize or support dedicated image related metadata, making it by design the least technically complex distribution format with the intent of keeping equipment cost low.

HLG is defined for several broadcast standards of different geographic regions such as in ATSC 3.0 and Digital Video Broadcasting (DVB). Further, HLG is supported by HDMI 2.0b, as well as the video codecs H.265 (HEVC), VP9, and H.264/MPEG-4 AVC.

B33.9.2.1.2 HDR10

HDR10 is an HDR format that uses the absolute PQ EOTF (see section B33.5.3.1) quantized in 10 bits. Further, it uses color gamut containers with ITU R BT.2020 color primaries. The format provides static image related metadata following the SMPTE ST 2086 standard. The fundamental properties such as the EOTF and colorimetric properties are consolidated in ITU R BT.2100. It is likely the most common HDR standard and is widely supported by content creation and deployment tools as well as TVs and home source devices such as set-top boxes, games consoles, etc. An HDR10 signal can be encoded via many modern compression formats such as H.264 and H.265 (HEVC), VP9, Apple ProRes and many more. Further, transport via HDMI is described in CTA 861.3 ('HDR Static Metadata Extensions').

It is important to note that HDR10 does not specify tone-mapping approaches. Therefore, if tone mapping is required, its implementation and behavior is up to the display manufacturer. This is significant in the context of metrology as the tone mapping behavior is usually intertwined with the actual display response properties, making it challenging to separate the impact of each on a measurement. Therefore, if a display rendering HDR10 does not track the PQ EOTF, it might be challenging to deduct the cause.

B33.9.2.1.3 Dolby Vision™

Dolby Vision™ is an end-to-end ecosystem imaging format created by Dolby Laboratories, Inc. The system was initially designed to apply to PQ but has been extended to support HLG as well. Bit depths up to 12 bits are supported. Frame accurate metadata is attached to the video signal. The metadata is created from both statistical analysis of the video;



additional manual input by the content creator can be provided as well. Dolby Vision™ display management employs a dedicated tone-mapping engine that tailors a mapping curve based on the metadata and the display's capabilities. This includes real-time adjustments to guide the tone mapping, e.g., to ambient light, taking into account display reflectivity and surround effects (for more on ambient effects, see section B33.9.3.2 as well as IDMS section 3.5.2).

B33.9.2.1.4 HDR10+

HDR10+ is a High Dynamic Range (HDR) technology that adds capability to HDR10 by adding dynamic metadata that characterizes the scene luminance with statistics. HDR10+ metadata is delivered frame accurately using an ITU-T T.35 message in encoded video streams and as a Vendor Specific InfoFrame (VSIF) over HDMI and DisplayPort. Displays that recognize HDR10+ can use the dynamic metadata to guide their adjustment of content to their display capability on a scene-by-scene or even frame-by-frame basis. HDR10+ supports codecs such as HEVC, AV1, WebM/VP9, with the full luminance range of PQ and bit depths supported by encoders.

B33.9.2.1.5 Technicolor SL1, 2, and 3

The ETSI standards TS 103 433-1 to 3 describe High-Performance Single Layer High Dynamic Range System (or SL-HDR) for use in Consumer Electronics devices. SL-HDR Part 1 ('Directly Standard Dynamic Range (SDR) Compatible HDR System (SL-HDR1)') is designed to reconstruct an HDR signal from a single layer SDR video stream that can be delivered using SDR distribution networks and services that might be already in place. This is achieved by utilizing either static metadata defined by SMPTE ST 2086 or dynamic metadata defined by using the formats by Philips and Technicolor as defined in SMPTE ST 2094-20 and 2094-30, respectively. Further, Part 2 and Part 3 describe enhancements using the Perceptual Quantization (PQ) and Hybrid Log Gamma (HLG) transfer function, which are called SL-HDR2 and SL-HDR3, respectively.

B33.9.2.2 Delivery Paths

Figure 25(b) illustrates the three common delivery avenues for HDR content. They are Over the Top (OTT) by a streaming service provider, via traditional broadcast service, or offline via optical disc media.

OTT provides a point-to-point connection from distributor to the consumer via an IP packet system such as the internet. This approach enables varying quality and compression levels as well as immediate access to large content catalogs. It requires access to an internet connection with sufficient bandwidth to facilitate HDR content with acceptable quality.

Broadcast services, on the other hand, do not require an internet connection and can be accessed via cable networks or an aerial antenna. Current broadcast standards such as ATSC 3.0, ETSI (DVB), and ARIB currently describe broadcast approaches that can facilitate HDR. An offline approach to HDR content delivery is **UHD Blu-ray**, which can provide HDR signals on supported players and displays.

It is also possible to deliver HDR content to a compatible display device that was generated or rendered in real time. This includes computer generated content such as games or interactive content. Devices capable of providing real time generated HDR output include modern computer GPUs and operating systems as well as gaming consoles.

B33.9.3 Consumer Display

The final element in the imaging pipeline present in Fig. 25(c) is the actual display. This point of exhibition also includes all directly connected devices such as set-top boxes, gaming consoles, optical disc players, and so on. The display is at the end of the imaging pipeline, where the signal received via OTT, broadcast, or from disc is decoded and converted into light that can be perceived by the HVS in a particular viewing environment.

Historically, displays such as TVs rendered a received signal using a single approach which was determined by its factory design. This led to incompatibilities amongst different geographic localities that utilized different signal standards such as NTSC, PAL, or SECAM, and only one of them could be understood by a display as they were defined by the display hardware. There existed some simple adjustment options to change brightness, contrast, and color that allowed a user to adjust their preference, but they were not extensive. With modern display systems, ample processing power is available, and the displays can carry out computationally intense processes such as signal decoding, global, and even local tone-mapping, signal optimization, etc. Also, decoding different signal types is no longer a technical challenge as they are implemented in software.

B33.9.3.1 Display Signal and Preference Modes

Modern displays such as TVs but also mobile devices and computer monitors do not always render a signal to the actual color volume that is physically available. Instead, they implement different signal rendering and viewing modes that can impact how a received signal is processed and mapped on screen. Here, it is important to separate between **signal type**



modes such as ‘SDR’, ‘HLG’, ‘HDR10’, etc. and **viewing preference modes** with labels such as ‘Vivid’, ‘Standard’, and ‘Movie’.

The signal modes set a display into interpreting the received source signal correctly, as specified by each individual format. On consumer displays, switching between signal modes is automatic and determined based on the fundamental signal identification metadata (see section B33.6.1). A mode change typically impacts the display’s rendering color volume. With HDR modes, this color volume might represent the maximum extent but might change the internal processing with different EOTFs, tone-mapping approaches, and so on. In SDR, the color volume might be reduced to match the expectations of the particular formats such as ITU-R BT.709 and ITU-R BT.1886.

By comparison, viewing preference modes change the appearance based on viewer preference and need to be selected manually by a viewer. Common preference mode examples include ‘Vivid’ or ‘Standard’ modes which adjust the appearance of the input signal to cater to viewer preferences and expectations, but typically do not represent the intent of the source content. The mode most true to the input signal is labelled ‘Filmmaker’, ‘Cinema’, or ‘Movie’ mode. These modes target a dark viewing ambient environment, although it is still likely that a tone-mapping stage is active. Therefore, these modes are a good starting point for metrological assessments. Some preference modes also include manual ambient light compensation by, for example, changing the APL and black level for a high ambient. This is often labeled by added descriptions such as ‘dark’, ‘light’, ‘home’, or ‘reference’, to name a few.

One important aspect to mention is that the same preference mode labels might be present amongst different signal type modes. However, even though the conceptual properties are the same (e.g., more saturation in ‘Vivid’ mode) the actual behavior of the preference modes might not match. For example, an SDR vivid mode might map the SDR signal into a color volume that approaches HDR ones by amplifying contrasts and saturation levels. As there is color volume ‘headroom’ available, this can potentially be done without detail loss. For HDR vivid modes, the intent is also to increase contrasts and saturation. However, as the rendering is typically already using the full physical capabilities of the display, saturated colors or highlights might clip and compress more than in a reference mode.

B33.9.3.2 Viewing Environment Considerations

When making assessments about the performance of a display and its imaging pipeline, it is common to only focus on the signal and the display device while ignoring the effects of ambient illumination. Such an approach might be acceptable if the viewing environment does not contribute to the actual light output of the display, as is the case for a completely dark surround. Indeed, good display metrology explicitly controls and ideally eliminates any light that does not originate from the display under test⁵⁶. This approach not only provides an accurate environment for measurements but can also facilitate a viewing setup where the only limiting factor to picture quality is the capability of the display device.

As typical real-world viewing environments are rarely completely light controlled, ambient light effects have to be considered as ambient illumination has substantial effects on the visibility of details and perceived contrast for images being displayed [Bartleson 1967, Rempel 2009, IDMS section 5.30 and chapter 11, among others].

Traditional displays (e.g., globally backlit LCD or CRT displays) by themselves could not render very low luminance levels. However, it was still important to manage lighting conditions and low-light instrumentation as ambient light can impact metrological assessments even with those traditional display technologies. In the context of modern display systems that are capable of rendering luminance levels significantly below those of traditional displays, the presence of even less ambient light can negatively impact low luminance rendering. This is particularly true for emissive displays⁵⁷.

Both the level of illumination and its geometry with respect to the display have key effects on the perceived imagery. In particular, there are three primary effects the ambient illumination has on image appearance:

1. Black level elevation (from ambient light reflecting off of the display surface),
2. Light adaptation (adaption by the eye to surround light levels), and
3. Surround effects (luminance of the region surrounding the display).

Figure 26 summarizes the different scenarios that affect the perceived black level conditions for emissive displays. In a completely dark room, the display’s minimum luminance defines the black level (a). For current display technologies, the dominant factor affecting image fidelity is the ambient light reflecting from the display screen surface. It originates from

⁵⁶ It is worth mentioning that even if the room is completely dark, light emission from the display itself is a source of ambient illumination and with that can influence low-light measurements. Low-light instrumentation considerations are covered in ICDM Appendix A3.

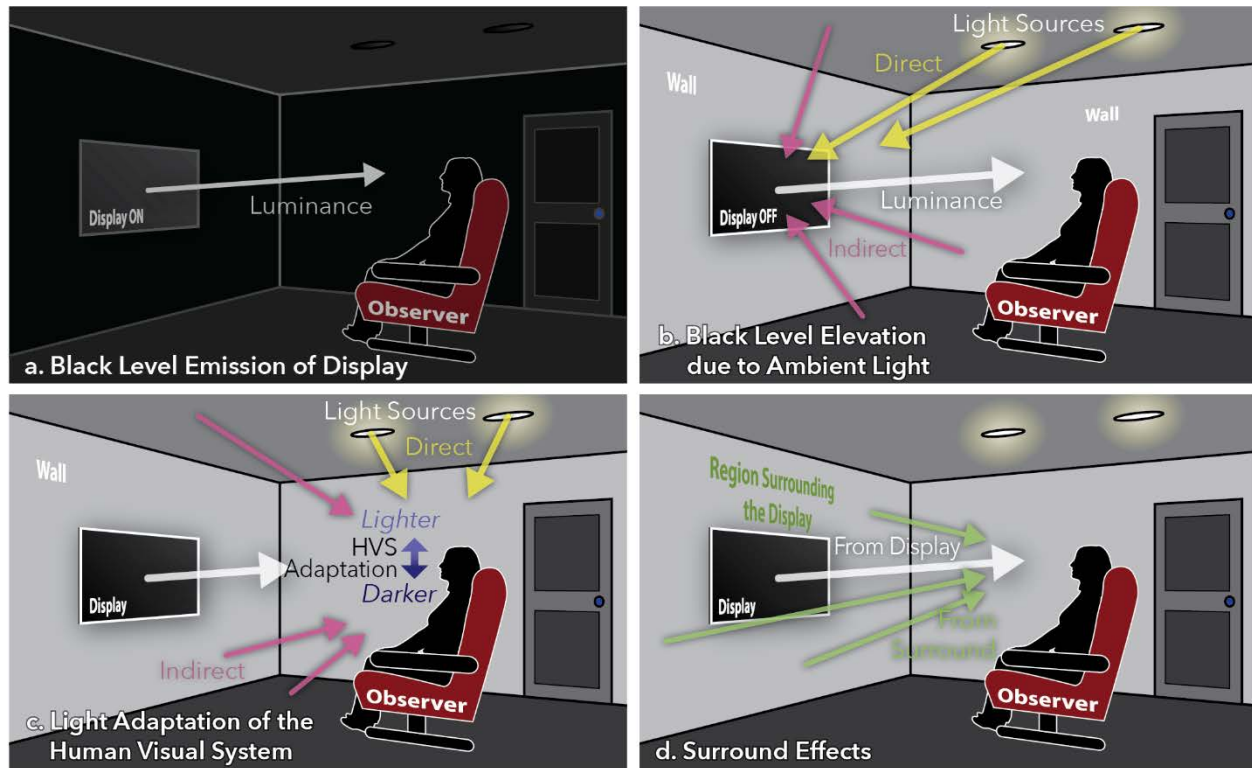


Fig. 26. Different types of illumination affecting image display quality; refer to [Daly 2019].

the illumination as well as from secondary reflections throughout the room, as shown in (b). If the ambient light is strong enough, the HVS will adapt to the prevailing illuminance as shown in (c). The adaptive processes are influenced by the light emitted directly from the display depicted by white arrow, direct visibility of the illumination (yellow arrows) and secondary reflections of the illumination illustrated by green arrows. The fourth example (d) illustrates the effect of surround light levels on glare and light adaptation (illustrated by the green arrows). Please refer to [Eda 2008, Daly 2013, Daly 2019] for more details on display black level and ambient properties.

If the visibility of deep blacks is impacted by any or all of the effects described in Fig. 26, it is possible to attempt to compensate the viewing experience, e.g., by actively lifting the display's black point or by changing the tone-mapping strategy. As described earlier, this can be facilitated in the simplest case by adjusting the display's brightness slider. Typically, using a daylight or home mode will improve fidelity even more (as described in the previous section B33.9.3.1). There also exist advanced approaches that utilize illumination sensors to adjust the impact of ambient light on the fly.

Note that the viewing distance and position may have an impact on image fidelity. For example, the perceptual impact of the area surrounding the display can change and with that impact how the HVS perceives the image displayed on the screen. This surround state may also interfere with any concepts of tone and gamut mapping. It is recommended to factor those properties into any consideration of perceived viewer picture quality. The reader is referred to IDMS Chapters 7 and 9 for more details on spatial resolution and viewing angle dependencies, respectively.

B33.9.4 Signal and Computational Precision

Fundamentally, an image pipeline signal⁵⁸ can use all code words available based on the signal's bit depth. For example, an 8-bit signal can address 256 integer steps from 0 to 255. This approach is called **Full Range** and is e.g., used when connecting a computer to a display. Depending on application, such as backwards compatibility, conformance to encoding schemes, etc., it is also common to apply small offsets to a signal. One prominent approach toward implementing such an offset is called **Narrow Range** (also referred to as 'Limited', 'Video', 'SMPTE' or 'Head' Range). With SDR signals encoded only in 8 bit⁵⁹ precision, this leads to Full Range (0 to 255) or Narrow Range (16 to 235). HDR imaging approaches

⁵⁸ The reference here is to an image signal, but the following is conceptually true for many signal transmission approaches.

⁵⁹ There exist approaches and formats that utilize 10 or 12 bits with SDR imaging pipelines and are used with high-end computer displays e.g., for CAD/CAM applications. A more recent implementation is 'Deep Color' (see HDMI 1.3 specification). Please also note that Deep Color can now also be used with HDR imaging formats to facilitate higher bit depths, e.g., via HDMI.



extend this to 10 or 12 Bits, leading to both bit depth differences as well as scaling options. This means that for example, the usable imaging signal levels do not start at 0 but rather at code word 64 or 256 for 10 or 12 Bits, respectively. Please refer to the main IDMS HDR chapter in section 20.1.4 or ITU-R BT.2100, Table 9, for detailed specifications.

Challenges arise if there are mismatches between Full or Narrow range, for example, if a signal offset is applied at the encoder side but not correctly removed at the decoder side. Incorrectly interpreting the signal scaling is a very common cause of error within imaging pipelines. If such an error is present, the effect on a display can appear similar to having a tone-mapping process applied. However, this error typically lowers image fidelity by reducing contrast or leads to unintended clipping and crushing of signal extremes.

Another potential source of inaccuracies might emerge when conversions amongst bit depths and Full or Narrow range have to be carried out. For example, ITU-R BT.2100 defines Narrow and Full Range quantization for RGB, YC_bC_r, and IC_TC_P at 10 bits and 12 bits, but not at 8 bits. Therefore, it appears obvious to only use of 10 and 12 bits with HDR-related metrology. However, this can cause problems when using video test and pattern sources. While many of those sources will output valid 10- and 12-bit signals, only 8 bits can be addressed by a user e.g., via calibration software or an API for communication with such a device. This might also include the frame buffer used to render test patterns, which is rendered in 8 bits and then converted to 10 or 12 bits before output e.g., to an HDMI output. At first glance, one can argue that even though there is a quantifiable benefit to using 10 or 12 bits for real imagery, a measurement granularity of more than 8 bits is indeed unnecessary for real-world metrological applications that use geometric test pattern. Another assumption is that a bit depth conversion is trivial. Indeed, calculations converting between Narrow Range encoding bit levels is straight forward. This can be achieved by simply adding and removing least significant bits. For example, the 8-bit narrow range from code value 16 to 235 exactly equals the 10-bit range from 64 to 940: the difference is only given by two additional least significant bits.

Full Range conversions on the other hand are more complex, especially when carried out with integer math. A 100% stimulus in 8 bits bears the signal level 255. With two least significant bits added, the value becomes 1020 and not the expected 10-bit maximum of 1023. Similarly, converting the maximum 10-bit value of 1023 to 12 leads to 4092 and not 4095. Finally, a bit adding conversion from 8 bit to 12 bit increases the error even further with an incorrect value of 4080 and not 4095. It is possible to carry out an accurate conversion between Full Range encoding bit depths, but this requires an intermediate step of converting to a normalized floating point or very high integer representation. The following example converts a Full Range 10- bit integer value x to the respective 12-bit value y :

$$Y_{(12\text{-bit uINT Full})} = \text{uINT12} \left(\frac{\text{float}(x_{(10\text{-bit uINT Full})})}{1023} \times 4095 \right). \quad (8)$$

Such approach is typically not common with current video devices, both with displays and signal sources, and they are therefore incapable of accurately converting between Full Range encoding bit depths because they operate with limited precision integer math. Therefore, if a metrologist is to use Full Range signals, it is essential that the output range is known and signaled correctly. Some source devices are incapable of outputting 10-bit signals and only offer 8- and 12-bit outputs as options. If the metrologist carries out accuracy calculations based on 10-bit Full Range, it is important to account for the inevitable error caused by the conversion from 10 bits to 12 bits in the source device. Such errors can, for example, introduce significant bias into color difference calculations (see section B33.9.6).

Another complication is with context to HLG, which has been designed to allow code values above 100% of Narrow Range as stated by Note 9a in ITU-R BT.2100: ‘Narrow range signals may extend below black (sub-blacks) and exceed the nominal peak values (super-whites) but should not exceed the video data range’. Note 9b in addition states that ‘some digital image interfaces reserve digital values, e.g., for timing information, such that the permitted video range of these interfaces is narrower than the video range of the full-range signal. The mapping from full-range images to these interfaces is application-specific.’ This suggests that some signal interfaces can be incapable of carrying Full Range signals correctly. Further, is common to decorrelate an image or video signal into Luma and Chroma components e.g., for storage and transmission (this, for example, facilitates approaches such as chroma subsampling). Therefore, dealing with image signals that are encoded in RGB or XYZ as well as decorrelated YC_bC_r or IC_TC_P does also require conversions amongst them. This again can lead to potential mathematical precision errors such as rounding errors and the potential for incorrect use of coefficients.

Another source of precision errors can originate from incorrect use of color space and EOTF transforms. It is crucial to use the correct transformation coefficients suitable for a given signal format. For example, a standard definition (SD) signal uses the ITU-R BT.601 standard and with that its color transformation matrices. High Definition (HD) content should instead use ITU-R BT.709. Similarly, BT.1886 and BT.2020 are not for HDR applications and BT.2100 should be used. If the matrices are applied incorrectly, errors will inevitably arise. Another source of error is the precision of those matrix coefficients and care should be taken that they match the appropriate standard.

Fundamentally, the final image quality and mathematical accuracy can be improved with workflows that involve the least number of mathematical image transforms or that provide high precision working spaces such as floating point or very



high integer bit depths. However, the metrologist can only control this issue to some extent as many conversion steps happen in the ‘black box’ of the display device.

B33.9.5 Interplay of Pipeline Elements

As covered in the previous sections, HDR imaging pipelines have been established and are now widely available to consumers. Compatible devices can be interconnected and HDR standards have been established to guarantee that imagery is rendered as intended. Nevertheless, as more devices with HDR capabilities are entering the market, problems can arise. These can impact the accurate rendering of a test pattern or ultimately the actual video content, especially if components are complex or if the HDR implementation is not common or mature. For example, Fig. 27 illustrates outputting a dedicated HDR signal from software running on a computer. In order for this example pipeline to present a correct image to the visual system as its ultimate recipient, all downstream pipeline elements such as the operating system, GPU driver, signal interface, and display must accurately interact in order to get the desired HDR imagery or test pattern rendered on the display. If the interplay of elements does not succeed correctly, the display might simply not show an image at all or provide an error message. However, it is also possible that the rendered image may be mapped to the screen incorrectly, with the wrong color space, EOTF, or signal spacing. If the image forming metadata is incorrect, this can be even more challenging to detect.

It is also worth noting that each of those example elements can by themselves be complex. For example, the display contains several building blocks such as the signal decoder, an image processing block, and a panel driving block. While each of those blocks might impact the signal, they are usually inaccessible to third parties (including the metrologist).

Therefore, when characterizing or calibrating a display device, it is recommended to reduce the complexity of the pipeline delivering an HDR signal to a device under test. Having as few pipeline elements as possible can minimize the impacts. Additionally, or alternatively, an assessment should be conducted to confirm all blocks are rendering correctly before starting measurements.

Figure 28(a) illustrates how a signal encoded with a PQ EOTF appears when correctly rendered on a display. If at some point in the signal pipeline the signal is incorrectly interpreted as having a gamma EOTF, then the most prominent visible sign will be desaturated colors, as shown in (b). The third example shown in (c) illustrates how the source signal would appear when rendered colorimetrically correct. This can be a problem or alternatively it could be as intended, for example, when rendering the source PQ signal on a reference display. The reader is advised that Fig. 28 only provides examples and that artifacts due to incorrect signaling can be more complex and less obvious to spot.

There are several HDR test pattern collections in the market that can help for troubleshooting and to confirm correct image rendering. They can be used via computer playback, direct attached storage such as USB sticks, or via UHD Blu-ray Disc. Several signal and test pattern generators, metadata injectors, and analyzers have also been released to the market that can be highly beneficial for troubleshooting.

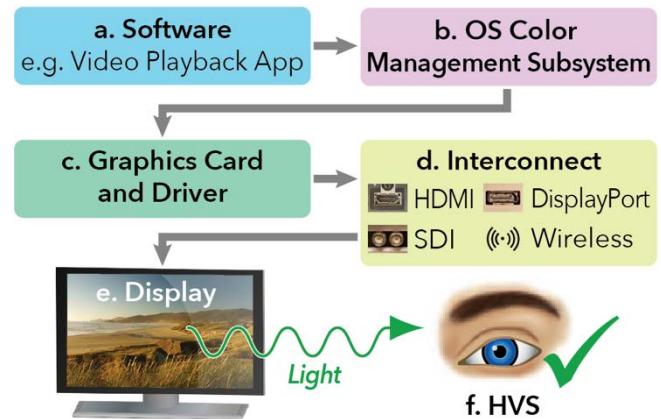


Fig. 27. Example imaging pipeline where the signal originates from a video playback app.

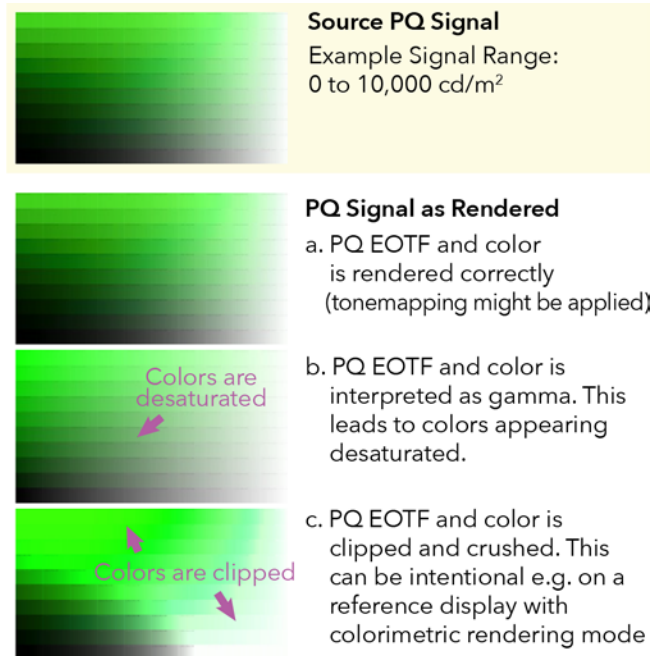


Fig. 28. Examples of proper (a) and incorrect (b) or potentially incorrect (c) rendering of a source PQ EOTF signal.



B33.9.6 Color Difference Methods

Another tool to determine potential errors are color difference metrics and they are an essential method in a metrologist's toolbox. The fundamental properties of such metrics are described in Chapters 6 and 8 in the IDMS. Please note that the topic of HDR-capable color difference methods is an active area of research within the scientific community as well as with standards development. To follow its mandate of providing a 'buffet' of options, the ICDM is not making recommendations as to which method to use.

The most common color difference methods used with display metrology are the patch-based steady state color difference methods such as CIE ΔE_{74} , ΔE_{94} and ΔE_{2000} , which are all based on the CIE 1976 $L^*a^*b^*$ color space (see section B33.5.5). Another common approach is given by the color difference method based on CIECAM02-UCS [Luo 2006]. With those methods, the adapting white point has to be provided or is assumed to be derivable from the display's peak white. Therefore, those models can be considered perceptually uniform in the context of this given adaptation point. A thorough discussion of those models is provided by Fairchild [2013].

The CIE Steady State Color Difference methods were originally not designed and verified to work with high dynamic range imagery. It is nevertheless possible that they can be used in the context of **frame or scene assessment**. For example, even if the content piece overall covers a large dynamic range bracket, an individual scene might be of lower contrast that is well within the steady state of the HVS. With that, the CIE ΔE methods can be applied, given that the adapting luminance reflects the scene's pixel distribution inside the HDR container. The scenes depicted by Fig. 12(c) and (d) exhibit such a lower inherent dynamic range even though they are part of an HDR content piece in an HDR signal container. Such individual scenes can therefore likely be assessed with steady state models⁶⁰. Fig. 12(e) on the other hand illustrates a scene that goes beyond the steady state and would likely lead to adaptive processes over the duration of observation. Thus, when dealing with imagery that offers very large physical contrast ranges such as most HDR imaging, there are several particularities such as spatial and temporal properties of the imagery that have to be considered. How to objectively approach such scenes is again under active scientific investigation.

Very large physical contrast range also comes into play when intending to assess the **capabilities of a modern display device**. It is not unusual for a contemporary display to span five orders of magnitude⁶¹ or more. In order to identify if such a display is capable of rendering any kind of HDR signal, that in the extreme case could span the display's full luminance range, the use of steady state models is limited as multiple, overlapping states of adaptation of the HVS would have to be considered to cover the display's overall dynamic range. Therefore, in order to provide an alternative option, the worst-case engineering approach discussed in section B33.5.3.1 can again be considered, which does not require the knowledge of a particular state of adaptation and instead assesses the display dynamic range based on detection thresholds. One such approach is provided by the ΔE ITP method, described by ITU-R Rec. BT.2124 ('Objective metric for the assessment of the potential visibility of colour differences in television').

B33.9.7 HDR Performance Specifications and Compliance

Besides delivery standards, several HDR performance labels have been established. In addition to providing narrow measurement methods and tolerances, their main use case is to classify the performance of a display device.

The open VESA DisplayHDR standard [VESA DisplayHDR] is a monitor and display compliance test specification that defines HDR performance capability, including luminance, color gamut, bit depth and rise time based on a set of measurements. It provides performance labels that can be used to indicate the expected display performance. Since revision 1.1., the specification contains the following performance thresholds emphasizing peak luminance (DisplayHDR 400, 500, 600, 1000, 1400) as well as black level ('DisplayHDR 400 True Black' and 'DisplayHDR 500 True Black'). More information can be found under www.displayhdr.org.

The UHD Alliance (<https://alliance.experienceuhd.com>) also provides a logo program to certify HDR display performance compliance with certain minimum thresholds. The labels named Ultra HD™ Premium and Mobile HDR™ Premium are assigned to display devices based on resolution, dynamic range, color gamut and accuracy, and bit depth consideration.

As note, the reader is reminded that the ICDM does not set performance thresholds. The purpose of the IDMS is to provide a 'buffet' of display measurement methods based on fundamental display metrology science and formed in conjunction with other standards bodies. To this extent, existence of the VESA and UHDA compliance criteria are included in this tutorial for reference only.

⁶⁰ Figure 12d spans a very low luminance window which might impact the performance of the CIELAB based ΔE methods.

⁶¹ Luminance decades. E.g., from 0.01 to 1000 cd/m².



B33.10 Summary and Further Reading

This tutorial provided an overview of the major elements encountered with an HDR ecosystem in context of modern displays. This overview included the discussion of the properties of HDR signals, common metadata approaches that can be used to improve the image fidelity, e.g., by using tone mapping to optimize an HDR signal to the capabilities of a target display. Further, typical properties of modern display systems were elaborated and how those displays interact with other elements of a typical HDR imaging pipeline.

There are many more aspects affecting an HDR imaging ecosystem that are beyond the scope of this tutorial. The following books are a useful extension to this tutorial by covering topics related to HDR such as image capture, human perception, color appearance, post-production and special effects.

- [Banterle 2011] Banterle, F., Artusi, A., Debattista, K. & Chalmers, A.: **‘Advanced High Dynamic Range Imaging: Theory and Practice’**, 2nd Edition. A. K. Peters, Ltd., Natick, MA, USA, 2011.
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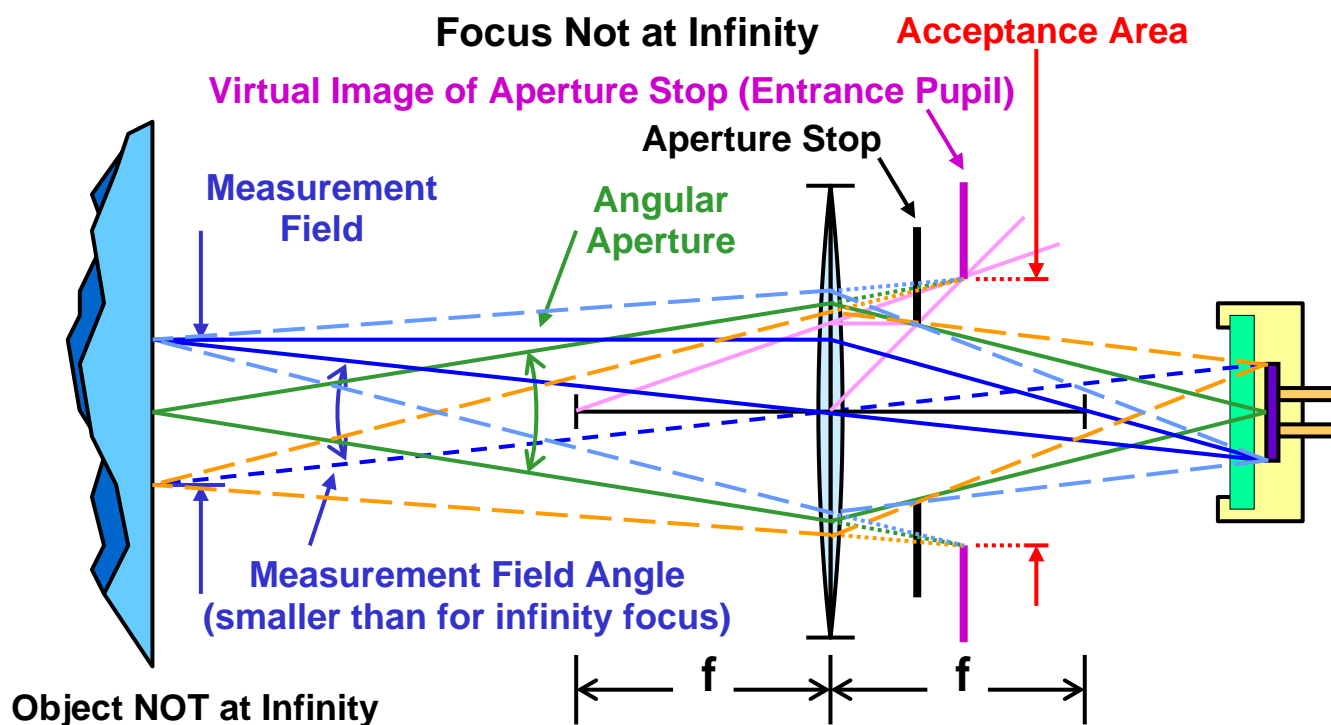
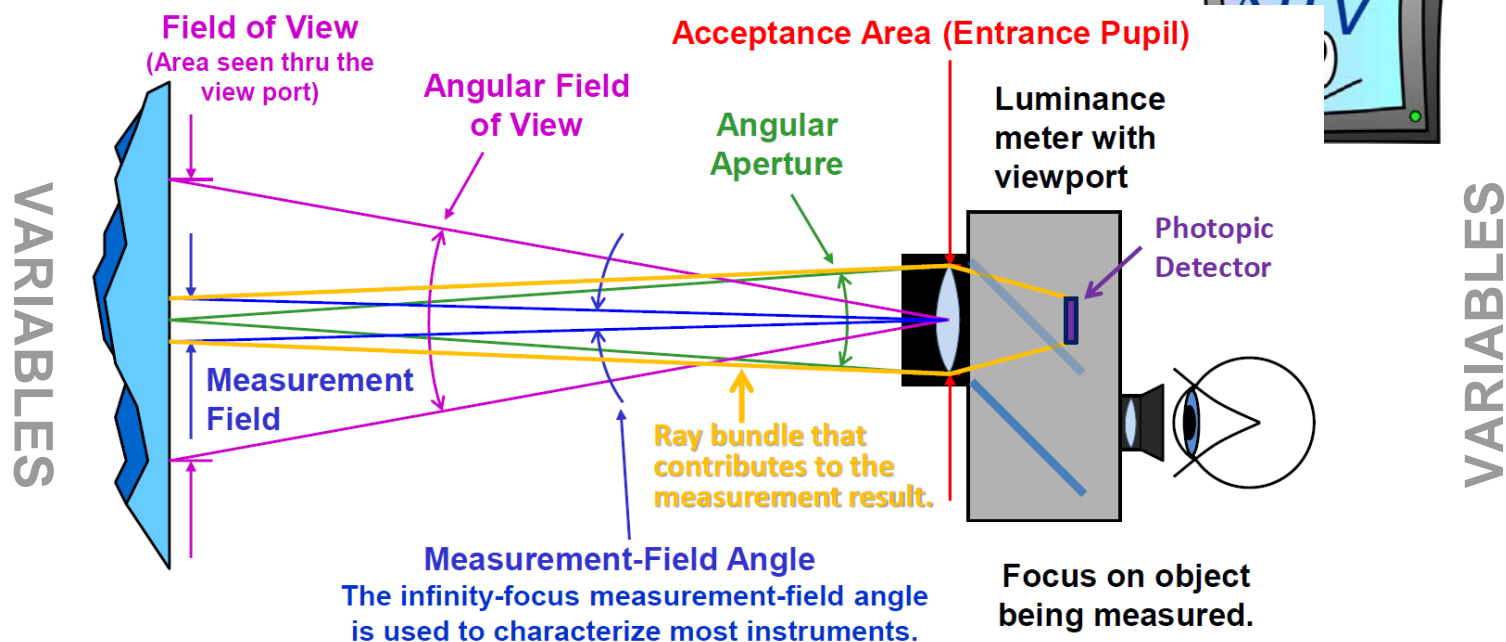
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C. VARIABLES & NOMENCLATURE

This section repeats content from the Chapter 3 Setup and places it all in one place. Not all these variables are used and not all variable are listed. This serves as a quick reference.



Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>.



Variables Used in This Document (Partial Listing)

Abbreviations: **LMD** = light measurement device or detector; **MF** = measurement field; **MFA** = MF angle; subpixel subscript *i* = red, green, blue, (R,G,B) for example, subscript *j* = bit or voltage level number.

α – aspect ratio ($\alpha = H/V$), measurement-field angle	N_H – number of pixels in horizontal dimension
a – small area, or small area of the screen	N_V – number of pixels in the vertical dimensions
A – area	n – an integer
B – bidirectional reflectance distribution function (BRDF), blurred-edge metrics	π – $3.141592653\dots = 4\arctan(1)$
c_d, c_s – distance from center of screen to detector, source	p – measure of distance on a screen in pixels
C – contrast (C = contrast ratio, C_m = Michelson contrast, etc.)	P – square pixel pitch (distance per pixel), power in watts (W), pressure
C – color in RGB or tristimulus components	P_H – horizontal pixel pitch
D – diagonal measure of the rectangular viewable display pixel surface that contributes to the display of information, also density, diameter	P_V – vertical pixel pitch
$\vartheta_H, \vartheta_V, \varepsilon_H, \varepsilon_V$ – north-polar and east-polar goniometer angles	q – luminance coefficient
η – luminous efficacy (of a source), north-polar goniometric coordinate	Q – cluster defect dispersion quality (1/cluster density); also a color W = white, R = red, G = green; B = blue; C = cyan, M = magenta, Y = yellow, K = black, S = gray shade.
ε – frontal luminance efficiency, east-polar goniometric coordinate	R – red, refresh rate, radius, reflectance factor
$E, E(\lambda)$ or E_λ – illuminance ($\text{lx} = \text{lm}/\text{m}^2$), irradiance ($\text{W}\cdot\text{m}^{-2}\text{nm}^{-1}$)	R – right (for 3D stereo chapter)
f – fractional fill-factor threshold luminance, time measured in frames	r, r_a – radius, radius of round small area on the screen
f_a – fractional (or percent) area of the screen for small area, target, or measurement field (MF)	s_i, s – subpixel areas, small areas, distances, size of edge of square, arc length
$\Phi, \Phi(\lambda)$ or Φ_λ – luminous flux (in lm), radiant flux (in W)	S – surface areas; signal level, or signal counts (as with using an array detector); also, square pixel spatial frequency (pixels per unit distance, $S = 1/P$)
H – horizontal size of the screen	S_H – horizontal pixel spatial frequency
\mathcal{H} – halation	S_V – vertical pixel spatial frequency
h – haze peak, height	θ, ϕ – spherical coordinates
γ – exponent in “gamma” construction of gray scale	θ_H, θ_V – horizontal, vertical viewing angles
$I, I(\lambda)$ or I_λ – luminous intensity ($\text{cd} = \text{lm}/\text{sr}$), radiant intensity ($\text{W}\cdot\text{sr}^{-1}\text{nm}^{-1}$)	θ_F – measurement field angle (MFA) of LMD or detector
k – integer, or detector conversion current per flux, e.g., A/lm, or $\text{A}\cdot\text{W}^{-1}\text{nm}^{-1}$	t – elapsed time, time
K, K – black, luminance (cd/m^2), radiance ($\text{W}\cdot\text{sr}^{-1}\text{m}^{-2}\text{nm}^{-1}$), kelvin (non-italicized)	T_C – correlated color temperature
λ – wavelength of light	T – transmittance factor
L^* – lightness metric in CIELUV and CIELAB color spaces	τ – interval between sample points measured in frames for motion blur, transmittance
\mathcal{L} – loading	V, V_j – vertical screen size, voltage, gray levels, volume
L – left (for 3D stereo chapter)	W, W – weight, symbol for watt (not italicized), white (not italicized)
m – integer, mass	Ω, ω, Ω – solid angle, ohm (not italicized)
$M, M(\lambda)$, or M_λ – luminous exitance ($\text{lx} = \text{lm}/\text{m}^2$), radiant exitance ($\text{W}\cdot\text{m}^{-2}\text{nm}^{-1}$), modulation transfer function	x, y, z – Cartesian right-handed coordinate system with z perpendicular to the screen, x horizontal, y vertical
\mathcal{N} – nonuniformity	\mathcal{U}, U – uniformity, uncertainty
N_a – number of pixels covered by a small area a	u', v' – 1976 CIE chromaticity coordinates
N_T – total number of pixels ($N_T = N_H \times N_V$)	u, v – 1960 CIE chromaticity coordinates (for CCT determinations)
	X, Y, Z – 1931 CIE chromaticity coordinates
	X – extinction ratio
	X, Y, Z – 1931 CIE tristimulus values
	$\bar{X}, \bar{Y}, \bar{Z}$ – 1931 CIE color matching functions



Variables Used in This Document (Partial Listing) — Continued

DETECTOR PARAMETERS

The detector when looking through a view port will be centered in that view port and held sufficiently far away from the view port so that it is not affected by veiling glare from bright areas. Not all parameters are independent.

c_d – distance of the center of the detector front surface (or lens) from the center (often z_d when detector is on the optical axis)

θ_d – inclination angle of detector from the z -axis

ϕ_d – Rotation or axial angle of the detector about the z -axis starting from the x -axis and going counterclockwise

R_d – radius of the entrance pupil of the detector

α – measurement field angle

m_α – measurement field diameter

x_t, y_t – Position where the detector is pointing or target position of detector in the x - y plane at which the detector is pointing. These can also be described using pitch, roll, and yaw angles ($\mathcal{U}_d, \mathcal{V}_d, \mathcal{W}_d$) from the ideal position with respect to the radius vector to the center and the horizontal plane.

F – The point at which the detector is focused (if so equipped). It can be a discrete variable as in either

focusing on the source or the display, or it can be a continuous variable where it is focused at some point along its optical path.

κ_d – subtense of the entrance pupil of the detector or angular aperture [$\tan(\kappa_d/2) = R_d / c_d$]

$\mathcal{U}_d, \mathcal{V}_d, \mathcal{W}_d$ – pitch (about the x -axis), roll (about the z -axis), and yaw (about the y -axis) angles (as determined by the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_t, y_t). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y -axis is pointing upward. Sometimes \mathcal{W} is used as a detector subtense when not used as a yaw angle.

SOURCE PARAMETERS (ALSO FILTER PARAMETERS USING SUBSCRIPT “f”)

Not all parameters are independent.

c_s – distance of center of the source exit port from the center of coordinate system (often z_s when the source is on the geometrical z -axis)

θ_s – inclination angle of the source from the z -axis

ϕ_s – rotation or axial angle of the source about the z -axis starting from the x -axis and going counterclockwise

R_s – radius of the source exit port (outer diameter of ring light source)

w_s – width of ring light source

θ_r – angle of ring light outer diameter from normal or angle of outer diameter edge of the exit port of a source positioned close to the display as measured from the normal [$\tan\theta_r = R_s / c_s$]

κ_s – subtense of source from the center [$\tan(\kappa_r/2) = R_s / c_s$], sometimes we use \mathcal{W} when it is not being used as a yaw angle.

x_s, y_s – target position of source in the x - y plane at which the normal of the source exit port is pointing. These can also be described using pitch, roll, and yaw angles ($\mathcal{U}_s, \mathcal{V}_s, \mathcal{W}_s$) from the ideal position with respect to the radius vector to the center and the horizontal plane.

$\mathcal{U}_s, \mathcal{V}_s, \mathcal{W}_s$ – pitch (about the x -axis), roll (about the z -axis), and yaw (about the y -axis) angles (as determined by

the right-hand screw rule about the axes) from the ideal position of the detector with respect to the radius vector to the center and the horizontal plane—see target position (x_s, y_s). The yaw angle direction defined here is opposite of those defined for aircraft because aircraft yaw axis is pointing downward whereas our y -axis is pointing upward. Sometimes \mathcal{W} is used as a source subtense when not used as a yaw angle.

U_s – average uniformity of the source luminance over the full extent of the exit port

For sources with view ports in the back side through which measurements are made:

R_v – radius of the view port

d_v – distance of the view port from the exit port of the source

c_v – distance of the view port from the center

κ_v – subtense of view port from the center

[$\tan(\kappa_v/2) = R_v / c_v$]

θ_v, ϕ_v – angles of the view port from the exit port center or from the normal of the display as with the diffuse illumination measurement (as defined for similar angles above)



DISPLAY PARAMETERS

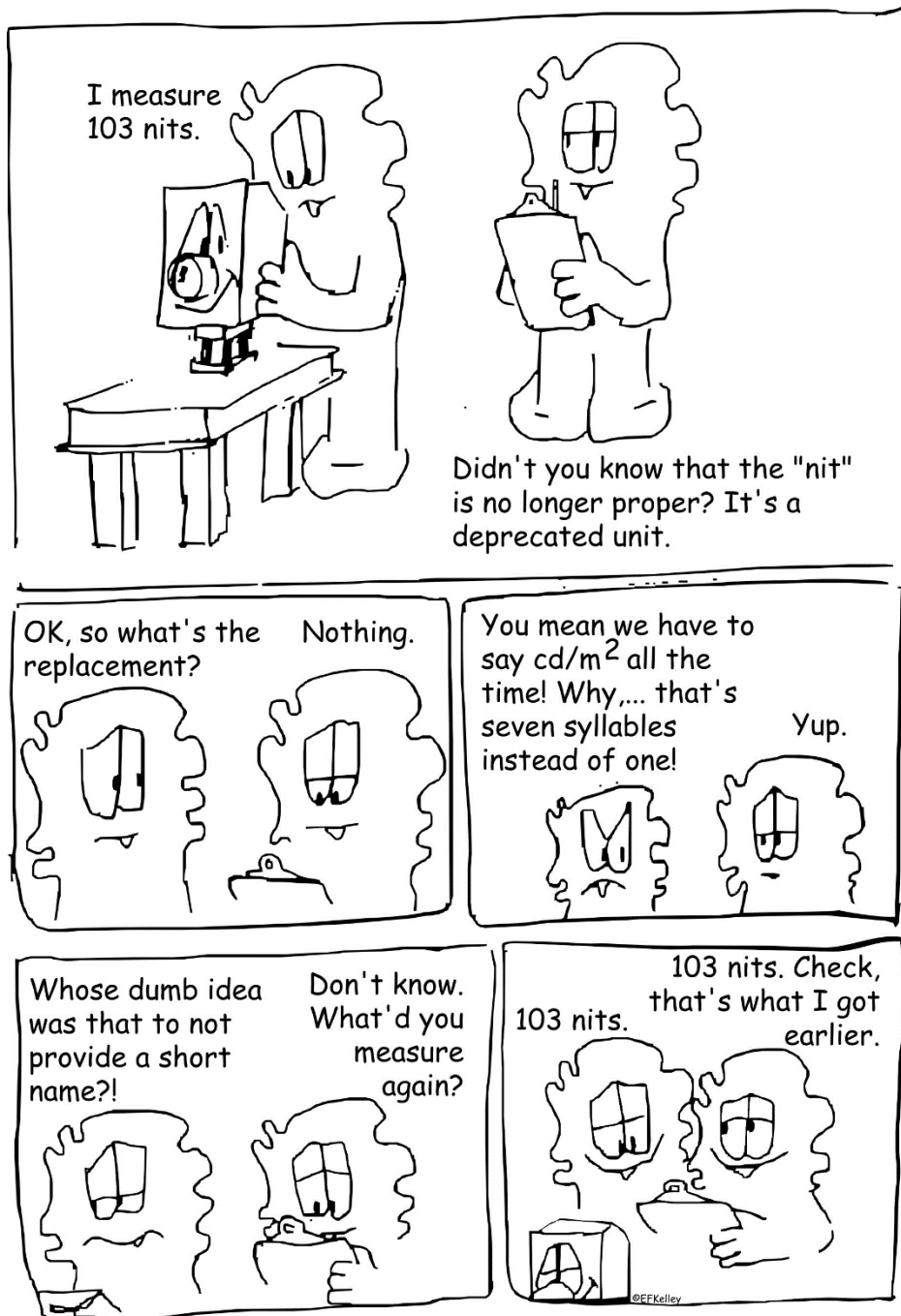
For any given pattern presented by the display, or for the display turned off. (6 parameters)

x_f , y_f , z_f – location of screen center (ideally, these should all be zero)

θ_f , φ_f , ψ_f – pitch, yaw, and roll orientation of the screen normal with respect to the z -axis and horizontal plane (ideally, these should all be zero)

VARIABLES

VARIABLES





D. GLOSSARY (See Chapter 17 for 3D Display Terminology)

α – Aspect ratio of a screen, the width-to-height ratio. See 14.1.2 Aspect Ratio for more details.

A – Area of a surface.

accuracy – The closeness of agreement between a test result and an accepted reference value. The qualitative term, when applied to a set of observed values, will have a random precision component and a systematic error or bias component. Since in routine use the systematic and bias components cannot be completely separated, the reported “accuracy” must be interpreted as a combination of these two elements. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA) See Section B21 for alternative nomenclature that is widely preferred.

addressability – The number of pixels in the horizontal and the vertical directions that can have their luminance changed; usually expressed in number of horizontal pixels by the number of vertical pixels, $N_H \times N_V$. This term is often used synonymously with resolution. For most purposes this is the same as the pixel array. However, with the advent of using subpixels to enhance the display of characters, the addressability has extended to a subpixel level.

AMLCD, AM-LCD – Active matrix LCD where each pixel (or subpixel) is powered by its own circuit or transistor affixed to the pixel.

angular field of view – The angle of the FOV in a detector with an eyepiece viewfinder as measured from the center of the acceptance area of the LMD; it includes the measurement field and the surrounding region visible in the eyepiece.

anti-glare (AG) – Controlling glare reflections from a display surface by distributing the specular energy in angles away from the specular direction because of a microstructure on the front surface that diffuses the light to some extent.

anti-reflection (AR) – Controlling glare reflections from a display surface by coating the front surface of the display with a layered coating to substantially reduce the specular reflections. This can be added to an AG surface to further reduce reflections.

array detector – Any of a variety of one and two-dimensional light detectors: Linear diode array, linear CCD array, CCD detector or CCD camera (two-dimensional array), CMOS arrays, and others. Often such devices have a substantial sensitivity to infrared light so that a photopic filter is needed to make accurate measurements of luminance.

aspect ratio – The ratio of screen width to screen height. See 13.1.2 Aspect Ratio for more details.

B – Abbreviation for blue.

background subtraction – The process by which a background signal is subtracted from a measured signal. If a stimulus is zero and a signal in the detector is produced (from thermal noise, for example) then this is the background signal. If that signal is added to the measured signal when a measurement is made as a stimulus is applied, better accuracy of the measured signal is obtained by subtracting off the background.

bias – a systematic difference between the sample mean of measurements or test results and an accepted reference value. Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA) See Section B21 for alternative nomenclature that is widely preferred.

bits per color – The number of bits available for each color, e.g., in an RGB system there may be 5 bits available for red and blue but 6 bits available for green which can be written as “5,6,5/RGB,” or “5R,6G,5B”; if 8 bits are available for each color then we could write “8ea RGB,” or simply “8 each.”

bkg, Bkgnd., bkgnd – Abbreviation for “background.”

black – The minimum luminance L_b attainable for the set conditions of the display. For example, with an RGB display, black is obtained when all three subpixels are at minimum luminance (smallest signal).

black gloss light trap – A gloss black surface, usually a narrow cone, used to provide a reference black in an area being measured. See “light trap” for more details.

black screen – A screen for which all pixels on the display surface are driven with the same stimulus in attempts to continuously display the same black level over the entire surface of the screen, where black means the minimum luminance that can be displayed.

blanking – The time interval used to identify and separate frames of video image information. During this time video image information is not being sent for display on the screen. It is a type of processing overhead.

K – Abbreviation for black.

blur – The spatial spread of an intended point, line, or area of light on a display screen. The term “blur” is used in optics to denote the degradation of images that are not in perfect focus; the image of a point is called a “blur circle” [See C. H. Graham, ed., Vision and Visual Perception (Wiley, 1966), pp. 518-520]. The term also applies to a display system. If the system is linear and shift-invariant, the blur of a point is mathematically described by what is known as the point-spread function.



Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>



BRDF – Bidirectional reflectance distribution function, the fraction of light from each possible incidence direction that is reflected in each possible reflecting direction; specifically, the ratio of the element of observed luminance in the direction of reflection to the element of illuminance from the surround. .

brightness – The visual and subjective quality of how bright an object appears – of how much visible light is coming off the object being perceived by the eye. Luminance is not a quantitative replacement for brightness. One should avoid confusing luminance and brightness: brightness is subjective, luminance is objective.

C_A – Ambient contrast ratio: the white-black full-screen center luminance ratio under diffuse ambient illumination.

C_G – Grille contrast ratio: the white-black luminance ratio of a series of equally spaced white and black lines.

C_L – Line contrast ratio: the white-black luminance ratio of a white line to a black line, a white line to a black screen, or a black line to a white screen.

C – Contrast ratio: the ratio of a white luminance to a black luminance L_w/L_b .

C – The color cyan.

C_m – Michelson contrast, contrast modulation: the ratio $(L_w - L_b)/(L_w + L_b)$ where L_w is the white luminance, and L_b is the black luminance. It is not a sensitive metric for comparing large contrasts.

C_T – Threshold contrast ratio: usually a minimum acceptable contrast for some condition, see § 9.2 for example.

Calc. – Abbreviation for calculate.

candela, cd – Unit of luminous intensity in lumens per steradian ($\text{cd} = \text{lm/sr}$)

CCD – Charge coupled device. A type of one-dimensional or two-dimensional light-detector arrays. (See array detector.)

CCT – Correlated color temperature: The temperature (in Kelvin) of the black-body radiator whose chromaticity (a point on the Planckian locus) is closest to the chromaticity of a particular light (e.g., from a display screen) as measured in the 1960 CIE (u, v) uniform chromaticity space. An algorithm for computing CCT, either from 1931 CIE (x, y) coordinates or from 1960 (u, v) coordinates, appears in G. Wyszecki and W. S. Stiles, *Color Science*, Second Edition, Wiley, 1982, pp. 224-228, where a graphical nomogram also appears. Alternatively, a successful numerical approximation has been derived by C. S. McCamy, *Color Res. Appl.* **17** (1992), pp. 142-144 (with erratum in *Color Res. Appl.* **18** [1993], p. 150). Given CIE 1931 coordinates (x, y), McCamy's approximation is $\text{CCT} = 437 n^3 + 3601 n^2 + 6861 n + 5517$, where $n = (x - 0.3320)/(0.1858 - y)$. This approximation (the second of three he proposes) is close enough for any practical use between 2000 and 10,000 degrees Kelvin.

cd, candela – Unit of luminous intensity in lumens per steradian ($\text{cd} = \text{lm/sr}$)

center of screen – The geometric center of the image-producing portion of the display surface.

chromaticity – a representation of the tristimulus values of a light with only two numbers computed so as to suppress via ratios the absolute intensity of the light. The two numbers (called chromaticity coordinates) define a space (called chromaticity space) in which any additive mixture of two lights lies on a straight line between those two lights.

CIE – Commission Internationale de l'Eclairage (International Commission on Illumination). In this document we use the 1931 CIE (x, y, z) chromaticity coordinates since they are most common. The users of this document may prefer some other chromaticity coordinate system. Feel free to use whatever system you want as long as all involved parties agree. We especially recommend the (u', v') 1976 CIE chromaticity coordinates since the color space is more uniform relative to the eye's sensitivity to color. In this document we use photometric symbols: Φ, I, L, E, M for luminous flux, luminous intensity, luminance, illuminance, and luminous exitance, respectively. Please don't confuse our symbol for luminance L with any CIE measures of brightness.

color – This really doesn't need a definition. We simply want to note that white, grays, and black are considered colors in this context. Strictly speaking white and gray are colors, black is the absence of light, but in most cases "black" is, in reality, dark gray. We use R for red, G or "grn" for green, B or "blu" for blue, W or "wht" for white, C or "cyn" for cyan, M or "mag" for magenta, Y or "yel" for yellow, K or "blk" for black, and "S" for gray shades. When speaking of R, G, B, for example, we mean the primary colors. When these are italicized they refer to level settings *R, G, B*.

color inversion (or color reversal) – Variation with viewing angle of the colors seen on a flat-panel display. Disturbances of the color relationships are more important perceptually than systematic changes, so a single number index of color reversal is the change in handedness of the chromaticities of three known test colors.

color management system (CMS) – A piece of software that converts the digital drivers (e.g., voltages) of color in one device so as to drive another device to produce the same color. Thus, the goal of a CMS is to convert the colors seen via device 1 (e.g., a CRT) to perceptually equivalent colors via device 2 (e.g., a color printer).

color sequential – A method of achieving a full-color display by sequencing frames of the different primary colors rather than having each pixel be composed of subpixels of each primary color.

collimation – Optical redirection of light so that all the rays generated or employed are traveling in approximately the same direction.

color depth – The number of digital bits allocated for each primary color.

color gamut – The set of colors producible by a color rendering device such as a display. For a three-primary display, the color gamut in chromaticity space is delimited by a triangle that is sometimes known as the RGB triangle. The area of such a triangle is called the color-gamut area and is variously defined in this document in CIE (x, y) space [Sections 2.7



and 5.19} or in CIE (u', v') space [Sections 5.16 and B.29], in ratio with different denominators. But strictly speaking, a color gamut is a set of colors, with no size metric imposed.

command – The digital signal level that electronically drives a subpixel, pixel, or group of pixels of a VDU. If a display has n gray levels available in the signal generation hardware and all these n levels are available to the software, then commanding a subpixel (or whatever) to level m means that the subpixel is driven at level m of the available n levels. The term “command level” is clearly for digitally driven displays. An equivalent term for analog displays would be “drive level” or “drive voltage,” depending upon how the display is driven. Synonyms for “command level” are “gray level” (though it may be confusing to speak of a gray level for a subpixel producing a color hence the preference for “command”), “bit-level,” as well as “drive level” or “command” without a modifier (as “we command the display to 255” meaning white in an eight-bit display). See “gray shade” and “gray scale.”

cross talk (crosstalk) – Primarily an electronic term designating an unwanted coupling between adjacent or nearby circuits whereby the signal properties of one element is injected into the other element of the circuit. Cross talk has also been applied to the mutual influence of image regions in displays which manifests itself in three principal ways: shadowing, ghosting, and streaking. (Synonym: cross coupling. See “shadowing,” “ghosting,” and “streaking”)

$\Delta u'v'$ – Color difference metric in the 1976 CIE color space. See A201 for details. $\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}$

D – Screen diagonal, diameter, duty cycle.

dark field correction – The subtraction of a background signal from the measured signal. Some detectors like CCDs have a background signal even when no light is present. To obtain accurate readings this background must be subtracted (pixel by pixel in the case of array detectors) from the measured signal. It is often measured by keeping the shutter closed or putting a black opaque (even to IR) cover on the imaging lens or aperture. (Synonym: background subtraction.)

darkroom, Drkrm. – A room in which stray light is carefully controlled or eliminated.

Daylight Eigenvectors – Spectra based on statistical observations of daylight that permit the estimation of the spectrum of a light from incomplete data about that light—e.g., from the light’s tristimulus values. Daylight eigenvectors, derived from a principal-component analysis of observed daylight spectral power distributions, are the eigenvectors of the covariance matrix of the observed spectra, and are ordered in decreasing eigenvalue. To perform spectral estimation using n input parameters, one should use the first n eigenvectors.

DHR – Directed hemispherical reflectance.

diffuse, diffusion – A diffuse surface is characterized by scattering of the incident light into many directions in the hemisphere before the surface. Examples are paper, matte paints, etc. A Lambertian surface is a perfect diffuser (it has the same luminance independent of the viewing direction—see “Lambertian”). Diffusion is the process of scattering light in directions away from directed ray (in transmission) or from the specular direction (in reflection). See ASTM E284.

design viewing direction, distance, point – Direction or position from which a display is designed to be viewed. For simplicity, this document specifies that the normal direction (perpendicular to the screen surface) always be used for measurements. However, we also recognize that some displays are designed to be viewed from a direction other than normal. Further, there may be a point in space from which the display has been designed to be viewed. An example of such a display is a privacy display that might be found on a bank-teller machine. If this document is used for measuring such a display, any non-normal design viewing direction or point must be clearly stated and agreed upon by all interested parties. It is left to the reader to make appropriate modifications in procedure to accomplish this. For example, in making uniformity measurements when a design viewing point exists, the luminance meter will be positioned so that its optical measurement axis is always looking at the positions on the display surface with the optical axis going through the design viewing point in space.

direct-view display – A display for which the image or information generated by the pixel or image-producing surface is viewed without intervening instrumentation or apparatus, e.g., TV sets, computer CRT monitors, FPD desktop monitors, laptop computer displays. You are looking directly at the pixel surface and whatever covering material is employed to protect the pixel surface. There are no lenses involved such as with head-mounted, head-up, or projection displays. Lenticular microlenses in near proximity to the pixel surfaces are in the direct unassisted view and do not exclude the displays from being considered as direct view displays.

display – An electronic device that presents information in visual form, that is, produces an electronic image—such as CRTs, LCDs, plasma displays, electroluminescent displays, field emission displays, etc. (Synonym: electronic display, DUT)

display surface – The physical surface of the display which exhibits information. (Synonym: screen)

dithering – A method of mixing pixels over an area of the screen where the pixels are given different luminances or colors within the area in order to create a luminance or color which cannot be obtained by an individual pixel.

dot – Basic unit of image spatial structure, a term adapted from printing. This term can be ill-defined since there is confusion as to whether it refers to the full-color pixel or the subpixel. As best we can determine it is often used to mean each discrete primary colored element composing a full-color pixel or the subpixel. We strongly suggest the use of the term “subpixel” instead. (Synonym: subpixel)

DPI – Literally “Dots per inch,” but also known as “lines per inch” or “pixels per inch,” to confusing effect. For square pixels it is assumed to be the same horizontally as vertically. Although dots may sometimes be considered to be



subpixels, DPI usually refers to full pixels capable of the full color reproduction of the display, i.e., pixels per inch. We strongly suggest the use of the term “pixels per inch” instead of DPI to eliminate any possible ambiguity.

drive level, drive voltage, drive current – The analog signal, voltage, or current that enables the display to change the luminance or color of the pixels. For example, in the case of an analog signal the luminance at a pixel might be a function of the applied voltage. Often the “drive” term is used with reference to analog signals whereas we try to use “command level” to refer to the bit level in a digital display.

driving stimulus – The signal, voltage, current, or bit count – whatever – that enables the display to change the luminance or color of the pixels. The vague term “driving stimulus” is used whenever we didn’t want to specify either a digital or analog excitation for the display.

DSO – Digital storage oscilloscope.

DUT – Display under test.

duty cycle – The on-time divided by the on-time plus off-time: $D = t_{on}/(t_{on} + t_{off})$.

DVM – Digital voltmeter.

Dwn. – Abbreviation for “down.”

Eff. – Abbreviation for “efficiency.”

E – Illuminance in lux, $lx \equiv lm/m^2$.

EIAJ – Electronics Industries Association of Japan.

EL – Electroluminescent display technology for which film phosphors fluoresce from ac or dc currents.

entrance pupil – The full diameter of the light gathering aperture of an instrument, e.g., the diameter of a lens.

Φ – Luminous flux in lumens, lm.

FED – Field emission display technology for which each subpixel has an individual field-emitting protrusion electrode that activates a phosphor from electron bombardment.

field – See “frame rate.”

field of view (FOV) – The area that is observable through the eyepiece of an LMD equipped with an eyepiece. It contains the measurement field and the visible region around the measurement field. Abbreviated: FOV. See angular field of view, which is the angle of the FOV as measured from the center of the acceptance area of the LMD.

fill factor – Various definitions have been attached to this term. Most simply, the fill factor—often expressed in percent—is the fraction of the area allocated to a pixel which actually produces luminance. Given a display which has N horizontal pixels and M vertical pixels spread over an area A of the display, the area allocated for each pixel is $a_p = A / (NM)$. Because of support structures, masks, etc. only a fraction of this area may serve to produce luminance, and that fraction f is the fill factor: $a_l = f a_p$. This is all very simple when the luminance-producing area is relatively uniform and geometrically well-defined. But when it is not so well-defined the definition of the fill factor is not generally agreed upon. The luminance from such a pixel is an average: $L_a = (1/a_p) \iint L(x, y) dx dy$, where the integration is carried out

over the allocated pixel area a_p . There is an associated maximum luminance of the pixel at some position (x_0, y_0) , call it $L_p = L(x_0, y_0)$. The fill factor is the ratio of the area of the region for which the luminance is above some chosen threshold luminance level L_t to the area allocated to the pixel a_p : $f = (1/a_p) \iint U(x, y) dx dy$, where $U(x, y)$ is a criterion function

which is nonzero and unity only where the luminance is at or above the threshold, i.e., $U(x, y) = 1$ whenever $L(x, y) \geq L_t$ and $U(x, y) = 0$ for $L(x, y) < L_t$. Often the threshold is taken as some fraction of the peak luminance: $L_t = \xi L_p$. Some choose the 50 % luminance threshold which is easy to measure using a spatially resolved luminance measurement system. We would argue that since the eye is a nonlinear detector, it makes much more sense to use 20 % or lower level for the threshold (some like 10 % or even 5 % to indicate a width) since the eye would perceive about a 50 % brightness falloff at 20 % of the luminance. When color subpixels combine to make a single pixel, use the luminance relative to the peak luminance for each subpixel and then sum the results for each subpixel to produce the fill-factor for the entire pixel which yields a higher fill factor than if the same luminance criterion is used for all subpixels. The higher result is believed to be a better representation of how the eye would evaluate the fill factor; for example, although a blue subpixel may be very dim compared to a green subpixel, the 10 % level of the blue “combines” with the 10 % level of the green and the 10 % level of the red to produce 10 % of white. It is in this sense that the 10 % blue level is, therefore, just as important as the 10 % green level.

flare – See “veiling glare.”

FOV – See “field of view.”

frame rate – The maximum frequency in Hz at which video information can be changed, except if the display employs interlace. For a display with interlace, the maximum rate is called the field rate and several (normally two) fields comprise a frame. For example, when two fields comprise one frame and the field rate is 60 Hz, the frame rate is 30 Hz. Frame rate or field rate refer to the rate at which information can be presented to the viewer—often between 59 and 96 Hz. Some displays that have a 60-Hz frame rate may be run at 120 Hz to reverse the polarity of the pixels, but the information can be changed only at 60 Hz. Some color sequential displays operate at 180 Hz, but the information is changed at the frame rate of 60 Hz.



FWHM – Full-width half-maximum: When considering a bell-shaped curve (or a similar peaked curve) the full width of the curve based upon its maximum value is often of interest.

gain – The ratio of the luminance of an image on the screen relative to the luminance which would be seen from a perfectly reflecting diffuser for a particular direction of observation.

gamma curve, gamma, electro-optical transfer function, tone-response curve – The luminance output relative to maximum of a display as a function of the digital input to that display. Historically the function has been modeled as a power function with power γ (hence the name). Later this model was modified by various gains and offsets, and still later the native display function was used to command other functions via lookup table—e.g., the DICOM GSDF. However, the name gamma is still used for the generic input-output relationship for a display. Two implicit assumptions still underlie the notion of gamma curve: The same gamma curve applies to all color channels in a display, and the relative spectrum of any color channel is invariant to change of the digital input

gamut-area metric – Area in uniform chromaticity space (u', v') subtended by the triangle of R, G, B primaries of an additive-primary display system. The gamut is expressed as a percentage of the total area subtended by the spectral-color “horseshoe” in (u', v') space.

gray level – The input stimulus to produce a certain gray shade. It can also refer to the number of command levels available to a device, such as an eight-bit display with 256 gray levels from 0 to 255. Some prefer to use the term “command level,” “command,” or simply “level” whenever referring to the level at which a pixel or subpixel is driven. (See “command” in this glossary). However, especially when referring to gray shades, the term gray level may be used whereby it refers to all subpixels being commanded at the same level in attempts to produce a gray color. “Gray level” will always refer to the stimulus. “Gray shade” will refer to the displayed result of the stimulus on the screen.

grayscale, gray scale – The electro-optical transfer function relating the input signal to the output gray shade. The relationship between the gray level (command level or bits in software) and the gray shade (luminance compared to white) is the gray scale. Given n gray shades that can be displayed on a screen, there are $w = n - 1$ levels above the zero level, denoted by level 0 for black, and level $w = n - 1$ for white. **Digital Signal Levels:** We often want to select a subset of m levels that are as evenly spaced as possible from this larger set of n levels. The interval between the w levels to create m levels is $\Delta V = w/(m-1)$, which may not be an integer. So, the levels to select are the (integer) values of $V_i = \text{int}[(i-1)\Delta V]$ for $i = 1, 2, \dots, m$, or $V_i = 0, \text{int}(\Delta V), \text{int}(2\Delta V), \text{int}(3\Delta V), \dots, \text{int}[(m-1)\Delta V]$, with $\text{int}[(m-1)\Delta V] = w$ for white. For example, in an eight-bit gray scale, there are $n = 256 = 2^8$ shades with the white level as $w = 255$. Suppose we want to select $m = 8$ command levels that are evenly spaced. The correct interval is $\Delta V = 36.4286$, and the chosen levels are: 0, 36, 73, 109, 146, 182, 219, 255. If we wanted to select $m = 32$ levels from the 256 shades, we’d use $\Delta V = 8.2258$ to give: 0, 8, 16, 25, 33, 41, 49, 58, 66, 74, 82, 90, 99, 107, 115, 123, 132, 140, 148, 156, 165, 173, 181, 189, 197, 206, 214, 222, 230, 239, 247, 255. **Analog Signal Levels:** For analog signals, if V_w is the white drive level and V_b is the black drive level, then for m levels the signal step size is $\Delta V = (V_w - V_b)/m$ and $V_j = V_b + j\Delta V$.

gray shade – The displayed shade of gray corresponding to a given gray level or command level. We use the letter “S” to denote a gray shade as a color.

halation – The leakage of light from bright areas of the image into the dark areas because of reflection or diffusion arising from the materials used in the construction of the display, their configuration, or cross-coupling in the circuitry that produces a corruption of black from surrounding white areas. Reflections off the covering material (e.g., front glass of CRT) and within or along the display surface (e.g., phosphor surface of CRT) are examples.

halo – The light that is scattered from bright areas of a display into dark areas usually appearing as a ring or outline surrounding the bright area. See Halation.

haze – The property of reflection that is like specular in that it is directed in the specular direction and is proportional to the incident illumination but does not create a distinct virtual image of the source. See also ASTM E284 where haze is connected with specular reflection manifesting itself as a reduction of contrast of the distinct image because of diffusion of the light from the strict specular direction.

HDTV – High definition television.

height – The vertical height V of the viewable screen actively producing an image.

hold-type displays – Displays in which the pixels when activated maintain their level (ideally, indefinitely) until readdressed to change to a different state. Many LCDs are hold-type displays.

I – Luminous intensity in candela, $\text{lm/sr} \equiv \text{cd}$

illuminance – The amount of light E falling upon a surface (or passing through a surface) expressed in lm/m^2 .

image – A display of information in the form of pictures of real-world objects or similar renderings usually having a continuous range of gray scales and colors. This is in distinction to graphics, see “graphics.”

imprecision – See “precision”—This is an imprecise term to use to describe uncertainty.

impulse-type displays – Displays in which the pixels are activated by a short pulse (or pulses) and return to their rest state after the pulse is applied. Generally, the on-time of the pixels is short compared to the refresh period of the display. Many CRTs are impulse-type displays.

inaccuracy – See “accuracy”—This is an imprecise term to use to describe uncertainty.



int(x) – The integer part of x . If $x = 3.8$, then $\text{int}(x) = 3$. Also, $\text{int}(-x) = -\text{int}(x)$.

integrating sphere – A hollow sphere with the interior surface coated with a white matte material usually of very high reflectance (but not always). It often has an entrance port for an input light source and an exit port to provide a source of luminance. If the exit port is 1/3 the diameter of the sphere or less and the interior white surface has a luminance factor of 98 % or more, then the nonuniformity of the luminance across the exit port can be nearly 1 % provided the lamp is properly baffled.

interested parties – All the companies and individuals who have negotiating authority in the commerce of an electronic display. This would include the user of a commercial display.

IR – Abbreviation for infrared radiation.

isotropic – Used to describe the nature of anything that has the same property in all directions.

JND – Abbreviation for Just-Noticeable Difference, a perceptually based unit of measure for the magnitude of difference between two stimuli. In JND units, two stimuli (e.g., an image sequence and a degraded counterpart) differ by 1 JND if an observer can discriminate between the stimuli with 75 % accuracy. There is a model based on human vision (called the Sarnoff Vision Model—see Lubin, et al., 1995, 1996) that predicts the discriminability (and perceptual difference) between two image sequences in JND units. Multiple JNDs can be interpreted as follows: a 1-JND difference has small perceptual impact; a 3-JND difference is almost always observable but not strong; a 10-JND difference is clearly observable. References: 1. J. Lubin, A visual system discrimination model for imaging system design and evaluation, in E. Peli (ed.), *Visual Models for Target Detection and Recognition*, World Scientific Publishers, 1995. 2. J. Lubin, M. Brill, and R. Crane, Vision model-based assessment of distortion magnitudes in digital video, presented at the November 1996 meeting of the International Association of Broadcasters (IAB).

K – Abbreviation for black as in CMYK—cyan, magenta, yellow, black. Also, Kelvin, the unit of absolute temperature (say “Kelvins” NOT “degrees Kelvin”).

L – Luminance in cd/m^2 . At one time this unit, cd/m^2 , was called “nit,” but that is no longer considered to be proper terminology. Please don’t confuse this with any of the CIE measures of brightness.

Lambertian – A property of a surface where the luminance is independent of the angle from which the surface is viewed.

landscape orientation – A display that is normally used with the widest edge of the pixel array arranged horizontally. See “portrait orientation” below.

L_b – Luminance of black.

L_w – Luminance of white.

LCD – Liquid crystal display, a display technology of which there are a number of varieties: active-matrix (AMLCD), thin-film-transistor (TFT), super-twisted-nematic (STN), etc. A liquid-crystal material sandwiched between electrodes (one of which is often transparent) that changes its reflectivity or transmissivity as a function of voltage.

lens flare – Please see “veiling glare.”

level – The signal used to produce a particular output luminance from a subpixel, pixel, or group of pixels. Please see “gray scale,” etc.

LMD, light measurement device – Any one of a variety of devices used to measure light, luminance, color, or color temperature. It can include a luminance meter, colorimeter, spectroradiometer, photodiode, photomultiplier tube, etc. depending upon the requirements for the measurement. Used interchangeably with “detector.” Other LMD’s include Spot LMD’s (such as photometers, photomultipliers, diode arrays, photodiodes, and photo transistors), Conoscopic LMD’s, and Imaging LMD’s (such as CCD or CMOS imaging devices as found in cameras).

light measurement device – See “LMD” above.

light trap – Any of a variety of objects that are used to provide a reference black in a region in which luminance (or color) is being measured. To obtain the blackest practical reference, use a gloss-black circular cone with a narrow apex angle where the apex of the cone is squeezed together or bent around so that there is no surface of the gloss-black material which faces the opening. When the requirement for a black reference is not so stringent, a gloss-black surface is employed. The reason for the glossy (specular) surface is that less light is likely to reflect from the environment into the LMD than would be encountered using a matte black surface. (Synonyms: black gloss light trap, black trap, black light trap, light trap)

linear regression – Method of computing the straight line that most closely fits a set of points. Given a linear functional form $y = mx + b$ suppose we have a number N of measurement pairs (x_i, y_i) and we want to extract the best coefficients m and b to fit these data. (For example, y might be the temperature of a furnace and x might be the time from turning on the furnace; we could measure the temperature as a function of time and desire to fit the data to a straight line so we can get an estimate of the rate of increase of temperature of the furnace m starting at the ambient temperature b .) The linear regression or fit of these data provide the following values for m and b :

$$b = \frac{1}{\Delta} \left(\sum_{i=1}^N x_i^2 \sum_{i=1}^N y_i - \sum_{i=1}^N x_i \sum_{i=1}^N x_i y_i \right), \text{ and } m = \frac{1}{\Delta} \left(N \sum_{i=1}^N x_i y_i - \sum_{i=1}^N x_i \sum_{i=1}^N y_i \right), \text{ where } \Delta = N \sum_{i=1}^N x_i^2 - \left(\sum_{i=1}^N x_i \right)^2.$$

The goodness of the linear fit is measured by the correlation coefficient r given by



$$r = \frac{N \sum_{i=1}^N x_i y_i - \sum_{i=1}^N x_i \sum_{i=1}^N y_i}{\left[N \sum_{i=1}^N x_i^2 - \left(\sum_{i=1}^N x_i \right)^2 \right]^{1/2} \left[N \sum_{i=1}^N y_i^2 - \left(\sum_{i=1}^N y_i \right)^2 \right]^{1/2}},$$

which can be positive or negative, but its absolute value is a maximum of one for a perfect fit and zero for no correlation (indicating that the data are random, not linear). These kinds of calculations are found in scientific calculators and spreadsheets.

loading – A change in the display performance that accompanies the change in power consumed by the electronics used in creating the image. For example, the white luminance displayed on a CRT can depend on the area of the white region being displayed: the larger the white area, the dimmer the white luminance. There can also be spatial distortions of the image because of loading effects.

Lum. – Abbreviation for “luminance.”

lumen – A quantification of visible light power, abbreviated lm.

luminance – Relates to the quantification of the colloquial technical term for the brightness of a surface. Luminance is expressed in cd/m².

luminance adjustment range – The range of adjustment in the luminance of a full-white screen provided as a control (software or hardware) with the display. (Synonyms: dimming range, percent of luminance variation, dimming ratio, brightness range, range of brightness)

luminance coefficient – The ratio of the luminance to the illuminance for a Lambertian reflector: $q = L/E$, where $q = \rho_d / \pi$, and ρ_d is the luminance factor.

luminance factor – The fraction of incident luminous flux reflected from a surface, often in reference to Lambertian reflectance where the luminance is related to the illuminance by $L = \rho_d E / \pi$.

luminous exitance – The amount of light M exiting a surface expressed in lm/m² (but not lux).

lux, lx – Unit of illuminance in lumens per square meter (lx = lm/m²) referring to light hitting a surface. Note that the lux is not a unit for luminous exitance (which is also measured in lm/m² but applies to light coming from a surface). The lux is used only for illuminance.

u_{LMD}, U_{LMD} – The combined standard uncertainty of the LMD and the expanded uncertainty of the LMD (usually with a coverage factor of two), respectively.

M – Luminous exitance in lm/m² (but not lux).

M – The color magenta.

major axis of display – The line through the center of the screen along its largest size of the pixel array. In the case of a landscape display it is the horizontal center axis. In the case of a portrait display it is the vertical central axis. See “minor axis of display” below.

matte – A reflection property of a surface that diffuses the incident light in quasi-Lambertian manner, i.e., the surface appears approximately the same brightness from all directions and there are not highlights or distinct reflections of sources. Often the term “diffuse” is also used in this manner. We speak of diffuse white standards and matte white paint: Both refer to the same kind of reflection, although when we speak of a diffuse white standard we generally mean a material that is as close to a Lambertian reflector as possible.

mean – The arithmetic average of a set of measurements. The mean (μ) of n measurements of quantities x_i is $\mu = \frac{1}{n} \sum_{i=1}^n x_i$.

Meas. – Abbreviation for “measure.”

measurement field (MF) – The region being measured by the LMD, often circular.

measurement field angle (MFA) – The subtended angle of the measurement field as viewed from the acceptance area of the LMD. When you purchase an instrument with a 1° measurement field angle, for example, the 1° refers to the measurement field angle at infinity focus.

MFA – Measurement field angle of an LMD, the angle from the LMD that subtends the measured region (often circular)—see § 3.7 and § A1.

Michelson contrast – An expression for the contrast given by $C_m = (L_{\max} - L_{\min}) / (L_{\max} + L_{\min})$, where L_{\min} is the minimum luminance and L_{\max} is the maximum luminance under consideration.

minor axis of display – The line through the center of the screen along its smallest size of the pixel array. In the case of a landscape display it is the vertical center axis. In the case of a portrait display it is the horizontal central axis. See “major axis of display” above.

Moiré pattern – An undesirable visible luminance modulation which has a spatial variation usually substantially larger than the pixel-to-pixel separation. It usually appears as a small quasi-linear two-dimensional luminance wave across a large portion of the screen. Moiré patterns are produced by two superposed sets of parallel lines that are slightly differently spaced or slightly inclined to each other.



moving-window-average filter – A linear operation that replaces each element in a one-dimensional input array by the arithmetic mean of ΔN successive input values starting at that input array element. For example, let the LMD sample rate be s , the raw time-dependent light measurements taken at intervals of $1/s$ be L_i , and define the window ΔN as the number of light data points over which an average is to be performed, then the resultant window-average-filtered signal for any data point i is S_i given by

$$S_i = \frac{1}{\Delta N} \sum_{n=i}^{n=i+\Delta N-1} L_n.$$

As this window-average filter moves along the data 0, 1, ..., i , $i+1$, $i+2$, ..., it creates a new set of data S_i from the original data. This process is referred to as subjecting the raw data to a moving-window-average filter, and the process manages to average out high-frequency irregularities which are narrower than the window width. (Also loosely termed a running average.) The moving-window average is a special case of a convolution; one retrieves a general convolution by replacing the above arithmetic mean by a weighted average.

monochrome – Property of a VDU that uses only one color to display its information (with or without multiple luminance levels). The VDU might show two colors, but the contrast used to display information is derived from only one color other than a background color. Some examples are black-and-white displays and blue-and-yellow displays, etc.

MPCD – Minimum perceptible color difference.

Munsell Colors – In this document eight reflectances are specified for unsaturated colors possibly useful in digital calibration of displays.

mura – A Japanese term adopted into English meaning nonuniformity or blemish (moo-rah' —“ah” as the “a” in “father”).

national metrology institute (NMI) – Each country has an organization for keeping track of the standards of weights and measures. For example, in the U.S.A it is NIST (National Institute of Standards and Technology, formerly the National Bureau of Standards); some others are ITRI (in Taiwan), KRISS (in the Republic of Korea), PTB (in Germany), NRC (in Canada), NPL (in U.K.), NIM (of China), INMETRO (of Brazil), etc.

native pixel array – The largest pixel array available to present information on a display. The term generally refers to using all the pixels to present information without scaling the image. It is the highest resolution that the display can offer in which each pixel can display the full range of colors. “Resolution” refers to the finest detail that the optical device (or eye) can see and should not be confused with pixel array. However, the term “resolution” used to describe the format is so ingrained in the display industry that we include it here for reference only. We would prefer that “pixel array” or “pixel format” be used instead.

NEMA DICOM (or NEMA, or DICOM) grayscale – A mapping from digital driving level to displayed luminance, designed so that equal steps in the digital driving level correspond to equal numbers of perceived just-noticeable differences (JNDs) in luminance. The scale was developed so that in all cases the JND of luminance would be as small as possible, so that medical images with quantization errors less than 1 JND would be guaranteed not to show visible quantization artifacts. The scale is referenced as follows: “Digital Imaging and Communications in Medicine (DICOM) 4: Grayscale Standard Display Function. National Electrical Manufacturers Association (NEMA) Standard PS 3.14-1999.”

N_H, N_V – Number of pixels horizontally, vertically.

NDF – Neutral density filter. See A113 Auxiliary Laboratory Equipment.

negative, negative screen, negative configuration – White (or bright) letters on a black (or dark) screen.

normal – The perpendicular to the surface of the screen. We specify that measurements should be made from the screen normal. Any other arrangement for a non-normal design viewing direction must be explicitly stated and agreed upon by all parties involved. See “design viewing” for a discussion of non-normal viewing of a display. (Synonym: screen normal, perpendicular to screen)

NTSC – National Television System Committee

OEM – Original equipment manufacturer. It usually refers to those manufacturers who integrate manufactured components together into a finished commercial product.

Opt. – Abbreviation for “optional.”

palette – The number of different colors that can be generated under all circumstances of use. Note that this can be a much larger number than the total number of colors that can be displayed at any given time. See “total number of colors.”

PC – Personal computer

PD, PDP – Plasma display, plasma display panel. A flat panel technology for which inert gas is ionized thereby producing ultraviolet light which, in turn, causes phosphors to fluoresce.

PDF – Adobe’s Portable Document Format® for electronic file reading of printed documents. Adobe’s reader is available from their web site for any major computer platform (www.adobe.com).

PE – Polyethylene

P_H, P_V – Number of pixels in the horizontal direction, in the vertical direction, which defines the active area of the screen.

photometry – Measurement of any quantity connected with the wavelength integral of an electromagnetic spectral power distribution, weighted by the CIE 1931 $V(\lambda)$ function.



- photopic, photopic response, photopic correction** – Transformation of spectral power measurements to luminous equivalents, through multiplication by the CIE 1931 $V(\lambda)$ weighting function, integration in wavelength λ , and multiplication by the appropriate conversion factor (e.g., 683 lumens/watt). If the light emitter is one square meter of Lambertian surface viewed from the normal direction, the luminous flux (in lumens) is numerically the same as the luminance in cd/m^2 .
- pixel array** – The array of pixels, usually rectangular, used to present information. People loosely refer to this as the display resolution.
- PMT** – Photomultiplier tube.
- portrait orientation** – A display that is normally used with the narrowest edge of the pixel array arranged horizontally. See “landscape orientation” above.
- PSF** – Point spread function—refers to the flux density in the image plane associated with a point source in the object plane of an optical system.
- PTFE** – Polytetrafluoroethylene (common trade name of Teflon®, a registered trade name of DuPont)
- percent change** – Given an initial value of a quantity Q_i and a final value of the same quantity Q_f , the percent change relative to the initial value is given by $100\%(Q_f - Q_i)/Q_i$; relative to the final value it's $100\%(Q_f - Q_i)/Q_f$.
- peripheral vision** – Vision with the part of the retina at least 14.5 degrees away from the eye's optical axis (see Wyszecki and Stiles, *Color Science*, 2nd Ed., Wiley, 1982, p. 89). In the peripheral retina, there are far more rods (dim-light-sensitive cells) than cones (bright-light-sensitive cells). Therefore, the perception of color and spatial detail is much less in the periphery than in the fovea. However, dim stars that are invisible in the fovea are visible using peripheral vision (especially near the inner margin of the periphery, about 20 degrees away from the optical axis--See T. Cornsweet, *Visual Perception*, Academic, 1970, p. 137).
- pitch** – The separation between the center of two adjacent pixels which is the same as the distance between identical points on two adjacent pixels. It is expressed in a distance/pixel such as 0.2 mm/px or just distance as 0.2 mm. This is the same as the reciprocal of the number of pixels per unit distance.
- pixel** – Picture element: A pixel is the smallest element of the display surface which can reproduce the full range of luminances and colors of the FPD. Often the pixel is composed of subpixels (or dots). (Symbol: px)
- pixel array** – Display format defined by an ordered pair comprising the number of pixels in the horizontal direction (N_H) by the number of pixels in the vertical direction (N_V). Some refer to this as the addressability or resolution. We prefer to use the term “pixel array” since a display may be using a different pixel array than its addressability. The term “resolution” refers to the eye's ability to see the pixels, not to the intrinsic number of pixels in the displayed array. Here are a number of pixel arrays currently specified (α being aspect ratio and N_T being the product of N_H and N_V) :
- positive, positive screen, positive configuration** – Black (or dark) letters on a white (or bright) screen (like white paper with black letters on it).
- power** – Rate of energy transfer in units of watts (joules per second). In electrical terms: power = voltage x current or $P = VI$.
- precision** –The closeness of agreement among test results obtained under prescribed conditions. Precision is the random component of accuracy. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA.) See Section B21 for alternative nomenclature that is widely preferred.
- primary colors** – The colors of the separate subpixels. In RGB displays the primary colors are red, green, and blue. In a chromaticity diagram these primary colors will lie at the corner points of the triangle representing the color gamut, within which is the white point. Our notation for the primary and secondary colors based on RGB is a single capital letter subscript: “R” for red, “G” for green, “B” for blue, “C” for cyan, “M” for magenta, “Y” for yellow. (Note we also use “W” for white, “K” for black, and “S” for a gray shade), e.g., L_Y , L_R , L_G , etc. Some displays include other subpixels as primaries such as white, cyan, yellow, and violet. In that case the geometry is more complicated.
- px** – Symbol for pixel.
- pt** – Abbreviation for a point.
- q** – Luminance coefficient of a surface whereby the luminance is related to the illuminance by $L = qE$. Usually, the reflection is implicitly assumed to be Lambertian, so the luminance doesn't change with viewing direction of the surface.
- Q** – Arbitrary color, L_Q where $Q = R, G, B, C, M, Y, K, W$, and S . Also used for defective pixels clustering quality.
- QTH** – quartz tungsten halogen, or QTH lamp. These are lamps that are used as stable light sources that are very reproducible in their performance.
- ρ** – Reflectance either expressed as a number or percentage.
- ρ_a** – Luminance factor: The luminance L of a Lambertian sample of reflectance ρ_a subjected to illuminance E is given by $L = E\rho_a/\pi$.
- ρ_s** – Specular reflectance: The luminance L from a specular (mirror-like) surface arising from a source luminance L_s is given by $L = \rho_s L_s$. If the source luminance L_s is at an angle of θ , the incident angle, from the perpendicular of the surface, then the direction of the reflected light, the specular direction, is the reflection angle $-\theta$ from the perpendicular where the perpendicular, the incident ray, and the reflected ray all lie in the same plane.



R_I – Symbol for residual image.

radiometry – The measurement of any quantity connected with electromagnetic radiation.

RAR – Resolution-addressability ratio—A ratio relating the spot size of a display to the pixel spacing. This ratio is the FWHM of a line (defined as resolution), divided by the inter-pixel distance (see TEB27 “Relating Display Resolution and Addressability,” EIA, 1988). NOTE: The inter-pixel distance used in this definition is not the same as the addressability (see definition of addressability), hence the term RAR is actually a misnomer. Direct-view LCDs have an RAR of less than unity, but other display technologies may not, particularly when there is optical spread (as in projection systems) or electron-beam spread (as in CRTs).

ray – The path of an infinitely narrow beam of light.

reflection – The process whereby luminous flux incident upon the surface of a display is redistributed with or without attenuation anywhere in the hemispherical area in front of the display.

refresh rate – The frequency with which a display updates the entire screen with video information electrically. This is not necessarily the same as the video frame rate and may include replication with repeated data. Note that in this document refresh rate refers to the rate at which each pixel is updated and not vertical refresh rate, which may exclude lines or some pixel information as part of the refresh.

repetition rate – The frequency with which an item is updated or pulsed. It can be the same as the refresh rate if it is synchronous or phase-locked or frequency-locked to the refresh rate.

repeatability – The closeness of agreement among the results of successive measurements of the same display, carried out in a single laboratory, by the same method of measurement, operator, and measuring instrument, with repetition over a specified period of time. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA.) An index of repeatability is the standard deviation of a set of measurements. See Section B21 for alternative nomenclature that is widely preferred.

replica mask – A black mask that has the same size and shape as a black area on the screen, that is used as a reference black to determine a suitable correction for glare.

reporting document, reporting documentation – Any reporting mechanism used to technically describe the performance or features of a display. It would include advertisements used to distinguish one display from another based on any measurement results from the use of this document.

reproducibility – The closeness of agreement among the results of successive measurements of the same display, but changing conditions such as operator, measuring instrument, laboratory, temperature, humidity, or time. The changes in conditions must be specified. (Adapted from ASTM E 284 Standard Terminology of Appearance, ASTM International, W. Conshohocken, PA.) An index of reproducibility is the standard deviation of a set of measurements. See Section B21 for alternative nomenclature that is widely preferred.

residual image – Partial remains of an image after the content has changed; the remnant of a video image on the screen after the original image is removed electronically. It is generally most pronounced when the image was unchanged for long periods of time, and/or had high contrast. The duration of the image to produce a residual image and amount and techniques for recovery are technology-dependent. (synonyms: latent image, image retention) Note: Testing for residual image could result in permanent damage to the display.

resolution – A measure of the ability to discriminate picture detail, i.e., ability to distinguish two adjacent spots on the screen. Sometimes resolution is defined as the full-width at half maximum of a line on a screen (see TEB27 “Relating Display Resolution and Addressability,” EIA, 1998). Unfortunately, resolution has been used interchangeably with addressability, but not in this document. If a display is poorly designed, it may have a large addressability, but adjacent pixels may not be resolved. See RAR (resolution addressability ratio) above.

RH – Relative humidity.

Ronchi ruling – A series of black opaque lines on a clear substrate (like glass) where the clear line width is the same thickness as the opaque line width. The ruling should always be observed from the ruling side in order to obtain maximum contrast. If it is observed from the substrate side then reflections in the substrate will degrade the observed contrast.

rounding – See “significant figures” below.

running average – See moving-window-average filter.

σ_{LMD} – The repeatability requirement placed upon any LMD used for measurements based upon this document.

s – Pixel spatial frequency, the inverse of the pitch, $s = 1/P$.

S – A subscript for gray shade.

screen – The physical surface of the display that exhibits information via electrically generated images. In general, it is the physical pixelated area, although in some cases, like projection display, it can be optically displaced from the actual pixel area. For direct view, fixed-format pixel displays, the image area will always be the pixel matrix. (Synonym: display surface, display face, viewing area, active area, active viewing area, viewable area)

screen height – The linear measure of the height of the displayable surface measured at center screen, the vertical height V.

screen normal – See “screen perpendicular” below.



screen perpendicular – A line which is normal or perpendicular to the surface of the screen; often the center of the screen is the reference point on the surface from which the perpendicular is determined. (Synonym: perpendicular, normal, orthogonal, screen normal)

screen width – The linear measure of the width of the displayable surface measured at center screen, the horizontal width H .

secondary colors – Combinations of two of the primary R, G, B colors at full intensity: For the RGB system they are cyan (B+G), magenta (B+R), and yellow (R+G) where we denote associated variables with three single letter capital subscripts “C” for cyan, “M” for magenta, and “Y” for yellow. Some displays include other primaries than RGB primaries such as a cyan or yellow subpixel.

shadowing – Cross coupling, or crosstalk, between any part of the pixel addressing architecture might occur in certain circumstances when there are images of varying luminances, or colors displayed. This could result in an image of one luminance level or color producing a shadow of equal or unequal luminance or color across some area of the display that has a different luminance level or color. (Synonym: cross talk, trailing, cross-coupling, streaking, ghosting. See “crosstalk.”)

sheen – The production of a distinct virtual image of reflected objects from a matte or diffusing surface when objects are viewed at grazing angles (angles far from the normal of the surface).

Shad. – Abbreviation for shadowing (see above).

SI – The International System of Units, universally abbreviated “SI” coming from the French *Le Système International d’Unités*.

significant figures & rounding – We should avoid being carried away in reporting too much precision in our measurement results. When we measure things or do calculations, there is no harm in recording and retaining whatever number of significant (or not so significant) digits is available, but reporting those results is a different thing. When reporting results, we have to worry about the number of significant figures we report, and we will generally need to do some rounding. In general, the number of significant figures to report must be no more than the least accurate number entering the calculation or, if reporting a measurement, the number of significant figures should be no more than warranted by the accuracy of the measuring instrument. Rounding conventions (unbiased rounding): If the digit(s) to round away are greater than 5, then round up; if lower than 5, round down. If the digit(s) to round away are equal to 5 and not greater, then round up if the preceding digit is odd, round down if the preceding digit is even. Examples:

7.03612 rounded to three significant figures is 7.04 because $612 > 500$.

7.03499 rounded to three significant figures is 7.03 because $499 < 500$.

7.03501 rounded to three significant figures is 7.04, because $501 > 500$.

7.03500 rounded to three significant figures is 7.04, because the digit before the 5 is odd.

7.04500 rounded to three significant figures is 7.04, because the digit before the 5 is even.

SMPTE – Society of Motion Picture and Television Engineers

solid angle – The ratio of the area of a portion of a spherical surface to the radius of that spherical surface.

spatial frequency – The number of items per unit distance. For example, if the separation between the center of two adjacent pixels is 0.2 mm (the pitch), then the associated spatial frequency of the display is the inverse of this: 5 (mm)^{-1} or 5 pixels/mm.

specular – Reflection without diffusion: A type of reflection whereby the luminous flux incident upon a display surface from an angle θ with respect to the normal is reflected in a direction θ on the other side of the normal directly opposite the incident angle. In this document it will usually refer to that part of reflection that produces a distinct (mirror-like) virtual image of the source. See ASTM E284 where it is defined as “reflection without diffusion, ..., as in a mirror.” Please do not confuse this with the haze peak (if haze exists).

specsmanship – A type of deception. A manufacturer or person is guilty of specsmanship if they deliberately measure a display or report a measurement result of a display in such a way to artificially enhance the reported specifications and characteristics of the display in order to sell more displays or make their display seem better than it is. This extends to those who deliberately misinterpret a measurement method or set-up condition in order to implement their attempts to mislead the unaware. To avoid specsmanship is why we specify in the Setup Section (3) that the display controls must not be changed during the course of the measurements, and that the display must be set up the way a trained observer who is not in the company would set up the display. You who do this kind of thing, specsmanship, know exactly what we are talking about; stop it! If you don’t stop it, the next version of this document will nail it down even harder.

specular reflectance – The ratio of the luminance of the specular virtual image to the source luminance for the component of reflection that defines a mirror-like distinct virtual image of the source: $\rho_s = L/L_s$.

spectrum locus – The locus of all chromaticities that come from monochromatic lights. Because it is substantially convex, the human spectrum locus is the boundary of physically producible colors.

sqrt – Square root function $\text{sqrt}(x) \equiv \sqrt{x}$, understood to be non-negative.



standard deviation – A measure of variation about the mean of a set of measurements. If there are n measurements of

quantities x_i , the standard deviation σ is defined: $\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \mu)^2}$, where μ is the mean.

Std., std., std – Abbreviation for “standard.” Usually associated with a white diffuse standard material having a known (calibrated) reflectance.

StDev. – Abbreviation for “standard deviation.”

STN – Super-twisted-nematic type of LCD.

streaking – Short-term or short-distance shadowing, which is a form of cross-talk whose effect decays over a distance on the display (see “cross-talk”).

subpixel – The smaller elements which can compose a pixel. For example, an RGB display can have each pixel composed of three subpixels: a red, green, and a blue subpixel (sometimes there are two green subpixels for a total of four subpixels per pixel). There can be other configurations than RGB; we are not limited to only three colored subpixels. Thus, a subpixel is each discrete primary colored element composing a full-color pixel. (Synonym: dot)

sunlight readability – Self-luminous displays that are sufficiently bright or that minimize reflections (or both) to be readable in direct sunlight that generally should include the diffuse illumination from the environment (sky, clouds, grass, etc.). It is important to realize that there can be a difference between specular sunlight readability (looking directly in the direction of the reflected image of light source) and sunlight readability referring to non-specular viewing (where the light source is positioned to not be in the specular direction). Sunlight readability without the diffuse component of illumination may be appropriate for displays used in outer space if they receive only direct sunlight. The term daylight readability may be a better term to use as it suggests the entire environment. For some displays the diffuse component of the daylight illumination corrupts the contrast to a greater degree than direct sunlight.

task – The conditions under which a display is used to achieve a particular purpose or goal. It can include the type of information that is displayed as well as the surround or environment in which the display and operator is placed.

text – Display output in the form of alphanumerics, usually with high contrast or good color contrast to make it as readable as possible.

TFT – Thin film transistor.

total color bits – The total number of bits available for color rendering (including grays). For a 5,6,5/RGB system we have 16 bits for the total color bits, the 8-bits each RGB system gives 24 bits for the total color bits.

total number of colors – The number of different colors that can be displayed at any one time. Thus, although a display may allocate 8 bits for each color RGB giving a palette of 16.78×10^6 colors, if only 256 of those colors can be allowed on the screen at any time, then the total number of colors would be 256. If we wanted to specify the palette in addition, we would say that there could be a total number of 256 colors from a palette of 16.78×10^6 colors.

tristimulus values – amounts of three primary lights that, when mixed additively, will match a given light to a given observer,

UV – abbreviation for ultra-violet radiation.

u, v – Chromaticity coordinates for the 1960 CIE color space.

u', v' – Chromaticity coordinates for the 1976 CIE color space.

Unif. – Abbreviation for “uniformity.”

v – Signal level, bit level, analog signal level

V – Vertical size (height) of the viewable screen actively producing an image (this assumes a rectangular screen). See *H* for horizontal size. Also, signal level, bit level, and analog signal level.

V(λ) – Spectral luminous efficiency for the human eye for photopic vision.

VDU – video display unit

veiling glare – Precise definitions may not be attached to this term or “lens flare,” but, in general, lens flare refers to strikingly non-uniform stray light that is introduced by reflections off the lens surfaces within a lens. Defined this way, lens flare is often very visible. (For example, when a camera is pointed in the general direction of the sun the bright illumination from the sun hits the lens and makes numerous rings, lines, and colored patches visible.) Veiling glare, on the other hand, is often used to refer to the less obvious and somewhat more uniform stray light that floods the entire region of the detector with light, corrupts dark areas with white (or color), or mixes colors. It can be introduced also by reflections within the lens system or scattering from dirt and other objects associated with the lens system.

video – In this document we often use “video” to refer to either a static or dynamic image produced on a screen. It can also be used to refer to the signal input to a display, or to represent electronic image producing technology, in general.

vignette – An image seen through a lens will be observed to get darker as you move further away from the center of the image on the axis of the lens. This type of darkening is called a vignette (French, pronounced: vin-yet'). The effect, either light or dark, is often used in portrait photography to soften the area around the face or bust and blend in the background. When imaging with a lens an aperture placed between the object and the lens can produce an out-of-focus image of the aperture with the image of the object within the out-of-focus or fuzzy image of the aperture. This fuzzy framing of the observed object is called a vignette.



warm-up, warmed-up, warm-up time – Refers to a minimum time interval after display startup before any measurements should be made for the purposes of this standard. The warm-up time is the time required for a display to reach luminance stability after it has been off for a sufficiently long time so that it starts at the ambient temperature at the turn-on time. Note that we recommend a 20-min warm-up time for standard setup. This test allows the user to either verify that the 20-min time is adequate or to determine if a different warm-up time is suitable or needed.

warm-up time measurement – A measurement of the time required to reach a certain luminance stability criterion for a specified screen condition such as full-screen white (not used in the Basic Measurement Suite).

width – The horizontal size H of the viewable screen actively producing an image.

window average – See moving-window-average filter.

white – The maximum luminance L_w attainable for the set conditions of the display. For example, with an RGB display, white is obtained when all three subpixels are at maximum luminance (largest signal).

white point – The chromaticity [e.g., with coordinate values (x, y) or (u', v')] of the light from a display screen at full activation of its (additive) primaries, as seen from the design viewing direction and in a dark room.

white screen – A screen for which all pixels on the display surface are driven with the same stimulus in attempts to continuously display the same white level over the entire surface of the screen, where white means the maximum luminance.

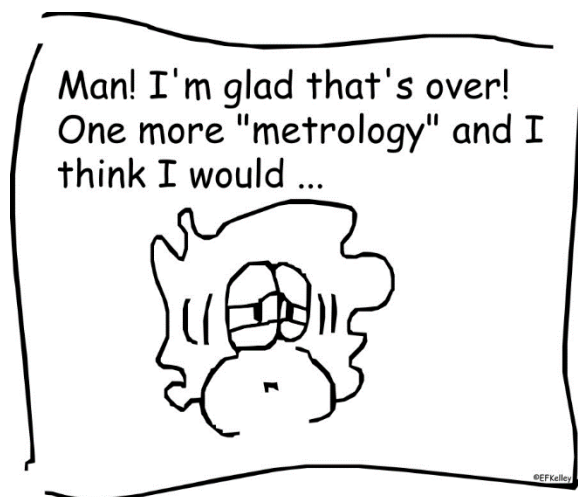
Wht, wht, W – Abbreviation for “white.”

WWW – Abbreviation for world wide web.

x, y, z – 1931 CIE chromaticity coordinates, derived from 1931 CIE tristimulus values X, Y, Z via the relations $x = X/(X + Y + Z)$, $y = Y/(X + Y + Z)$.

x, y, z – Right-handed Cartesian coordinate system with z as the axis normal to the display (assuming the surface is vertical), y is the vertical axis, and x is the horizontal axis.

Y – The color yellow.





E. ACRONYMS

ACRONYMS

AAPM	American Association of Physicists in Medicine
ACATS	Advisory Committee on Advanced Television Service
AEA	American Electronics Association
ALARA	as low as reasonably achievable
AMLCD	active matrix liquid crystal display
ANSI	American National Standards Institute
ARPA	Advanced Research Projects Agency (formerly DARPA)
ASTM	American Society for Testing and Materials
ASS	Swedish Nation Board of Occupational Safety and health
ATSC	Advanced Television Systems Committee
ATTC	Advanced Television Test Center (created by broadcasting companies and industry organizations in 1988 to test proponent advanced television transmission systems. Alexandria, VA)
ATV	advanced television
B-ISDN	Broadband Integrated Services Digital Networks
BIPM	Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
BRDF	bidirectional reflectance distribution function
BSDF	bidirectional scattering distribution function
BTDF	bidirectional transmittance distribution function
CATV	cable TV
CCIR	International Radio Consultative Committee
CCITT	International Telephone and Telegraph Consultative Committee
CCPR	Consultatif Comité de Photométrie et Radiométrie (Consultative Committee of Photometry and Radiometry)
CD	committee draft
CEN	Comité Européen de Normalisation (European Standards Committee)
CENELEC	European Committee for Electrotechnical Standardization
CGPM	Conférence Générale des Poids et Mesures (General Conference of Weights and Measures)
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
CIPM	Comité International des Poids et Mesures (International Committee for Weights and Measures)
CMS/ITRI	Center for Measurement Standards / Industrial Technology Research Institute (Taiwan)
COHRS	Committee on High Resolution Systems
CORM	Council for Optical Radiation Measurements
CSF	contrast sensitivity function
CSL	Computer Standards Laboratory
DAB	digital audio broadcasting
DARPA	Defense Advanced Research Projects Agency
DICOM	Digital Imaging and Communications in Medicine
DIN	Deutsches Institut für Normung (German Institute for Standardization)
DIS	draft international standard
DMS	Display Measurements Standard of the ICDM
DSRC	David Sarnoff Research Center
DUT	display under test
EBU	European Broadcasting Union
EC	European Community
EEC	European Economic Community (often use EC above as substitute)
EFTA	European Free Trade Association
EIA	Electronic Industries Association
EIAJ	Electronic Industries Association of Japan
ESF	edge spread function
FED	field emission displays
FCC	Federal Communications Commission
FPDM	Flat Panel Display Measurements Standard (VESA)
HDTV	high definition television
HRI	high resolution imaging
HRIS	high resolution information systems
ICDM	International Committee for Display Metrology
IDMS	Information Display Measurements Standard



ACRONYMS



IEEE	Institute of Electronics and Electrical Engineers
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
IS&T	Society for Imaging Science and Technology
ITRI	Industrial Technology Research Institute (Taiwan)
ITU	International Telecommunication Union
KRISS	Korea Research Institute of Standards and Science
LMD	light measurement device (in VESA FPDM)
LSF	line spread function
MAC	Multiple Analog Component
MPR	Swedish National Board for Measurement and Testing
MTF	modulation transfer function
MUSE	Multiple Sub-Nyquist Sampling Encoding System (Japanese HDTV system)
NAB	National Association of Broadcasters
NEMA	National Electrical Manufacturers Association
NIDL	National Information Display Laboratory (at Sarnoff Corporation)
NIST	National Institute of Standards and Technology (USA)
NMIJ/AIST	National Metrology Institute of Japan / National Institute of Advanced Industrial Science and Technology
NPL	National Physical Laboratory (UK)
NRC	National Research Council (Canada)
NRLM	Replaced by NMIJ, previously National Research Laboratory of Metrology (Japan)
NTIA	National Telecommunications and Information Administration
NTSC	National Television System Committee
OSTP	Office of Science and Technology Policy (part of the Executive Office of the President)
OTF	optical transfer function
PIMA	Photographic and Imaging Manufacturers Association
PSF	point spread function
PTB	Physikalisch-Technische Bundesanstalt (Federal Physical Technical Institute [Germany])
SAE	Society of Automotive Engineers
SI	Système International d'Unités (International System of Units)
SID	Society for Information Display
SMPTE	Society of Motion Picture and Television Engineers
SPIE	International Society for Optical Engineering (Society of Photo-Optical Instrumentation Engineers)
SSI	Swedish National Institute of Radiation Protection
STN	super twisted nematic (liquid crystal)
TAG	technical advisory group
TC	technical committee
TEPAC	Tube Engineering Panel Advisory Council (for EIA)
TEB	TEPAC Engineering Bulletin
TEP	Tube Engineering Panel
TFT	thin film transistor
TN	twisted nematic (liquid crystal)
USDC	United States Display Consortium
USNC	US National Committee of the IEC
VESA	Video Electronics Standards Association (vee'-suh)
VDT	video display terminal
VDU	video display unit
WG	working group, work group

Updates, supplemental material, and other IDMS material can be found at <https://www.sid.org/Standards/ICDM>



F.ACKNOWLEDGMENTS

F1.1 Version 1.03

Introduction: The ICDM committee is comprised of members of the international display community who have taken it upon themselves (volunteering in their spare time) to create this new Information Display Measurement Standard (IDMS). The ICDM IDMS document is a compilation of work from many contributors and content from previous standards (VESA). In creating this document, which can be used worldwide on any type of display, many new test methods have emerged. An attempt to acknowledge all participants and contributors follows, but there may be some that got missed and we wish to thank all who contributed to making this effort possible.



Top Level Acknowledgments: The entire committee would like to thank its chair, Joe Miseli (Oracle) for taking the lead in getting this document completed. His tireless efforts have been extraordinary, in traveling all over the world to conduct meetings, in creating and maintaining the web presence of the ICDM (<https://www.sid.org/Standards/ICDM>), in motivating the committee members to contribute, in the late nights and weekends, and many other ways. We also wish to thank Joe's wife, Gail, for her sacrifices in giving up so much of Joe's time. This document would not exist without his leadership.

Another main contributor that needs special recognition is Ed Kelley of KELTEK, LLC (formerly of NIST), and our Editor-in-Chief. Through long nights and many rounds of revisions he has been a steadfast mentor and guide for the authors. His experience in producing a quality and very comprehensive document shows in the final product. Without his unwavering persistence to detail, the documentation would have quickly become unmanageable. Thank you Ed for your heartfelt work to create such a well-structured document that you have poured your heart and soul into. We would also like to thank Ed's wife, Marva, for allowing Ed to spend time away from his daily routine to editing this most impressive document.

SID Acknowledgment: We would like to thank the Society for Information Display (SID) for bringing the ICDM committee into SID as part of the Definitions and Standards Committee and allowing us to develop this document to solve the needs of the display industry to create a single top-notch reference standard for how to measure and characterize displays. After leaving VESA and before coming to SID, the ICDM was an independent display standards group. We are grateful for the support given the committee. Through SID, this measurement standard will be available to a world-wide audience and will help to create an environment for display measurement standards to become more standardized throughout the industry. Thanks also to the SID Executive Committee for their help and support for business management issues to get the document released.

VESA Acknowledgment: We would like to thank the Video Electronics Standards Association (VESA) for allowing us to use content from their FPDM2 (Flat Panel Display Measurements) document. These earlier VESA documents, FPDM versions one and two (FPDM1 & FPDM2), were developed under the VESA umbrella with many of the same contributors that worked on this ICDM IDMS document.

Authors, Subcommittee Chairs, and Contributors for v 1.03

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02	Reporting	Ed Kelley (KELTEK) & Joe Miseli (Oracle)	
03	Setup	Ed Kelley (KELTEK) & Joe Miseli (Oracle)	Ray Soneira (DisplayMate), Mike Klein (Photo Research)
04	Visual Assessment	Joe Miseli (Oracle)	Isao Kawahara (Panasonic), Ed Kelley (KELTEK)
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	Volume Color Reproduction Capability	Jongho Chong (Samsung)	Brian Berkeley (Samsung)
06	Gray Scale and Color Scale	Don Gyou Lee (LG Display)*	Ed Kelley (KELTEK), Joe Miseli (Oracle), Robin Akins (Dolby)
07	Spatial	Ed Kelley	Bao-Jen "Andy" Pong (ITRI), Cheng-Hsien Chen (ITRI), Z.Y. Chung (ITRI), Kuei- Neng "Gilbert" Wu (ITRI), Yuh-der Jiaan (ITRI), Shau-Wei Hsu (ITRI)



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E	Acronyms	Many contributors.	
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F1.2 ACKNOWLEDGMENTS VERSION 1.1

Top Level Acknowledgments: The entire committee would like to thank its chair, Paul Boynton (formerly NIST) for taking the lead in getting this document completed. His tireless efforts have been extraordinary, in traveling all over the world to conduct meetings, in creating and maintaining the web presence of the ICDM (<https://www.sid.org/Standards/ICDM>), in motivating the committee members to contribute, in the late nights and weekends, and many other ways. This document would not exist without his leadership.

Another main contributor that needs special recognition is Ed Kelley of KELTEK, LLC (formerly of NIST), and our Editor-in-Chief. Through long nights and many rounds of revisions he has been a steadfast mentor and guide for the authors. His experience in producing a quality and very comprehensive document shows in the final product. Without his unwavering persistence to detail, the documentation would have quickly become unmanageable. Thank you Ed for your heartfelt work to create such a well-structured document that you have poured your heart and soul into. We would also like to thank Ed's wife, Marva, for allowing Ed to spend time away from his daily routine to editing this most impressive document.

Johan Bergquist is our new editor who actually saved this effort by his assembly of the final document. Ed Kelley retired and passed the baton to Johan. Johan has a sharp eye for detail, is very knowledgeable about displays and their measurements, and has good equipment for handling this huge document.

SID Acknowledgment: We would like to thank the Society for Information Display (SID) for bringing the ICDM committee into SID as part of the Definitions and Standards Committee and allowing us to develop this document to solve the needs of the display industry to create a single top-notch reference standard for how to measure and characterize displays. Thanks also to the SID Executive Committee for their help and support for business management issues to get the document released.

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10	Temporal	Mike Wilson*, Yoojin Kang, Don Gyou Lee, Sehyeok Park	Michael Becker, Johan Bergquist, Neil Robinson, Roland Seibt
11	Reflection	John Penczek*	Dirk Hertel, Ed Kelley
17	3D and Stereoscopic Displays	Adi Abileah*	Allen Earman, Johan Bergquist, Hyunki Hong, Hans van Parys
19	Near Eye Displays VR/AR, HMDs	Richard Austin*, Ryan Beams, Rick Brinkley, Michiel Callens, Allen Earman, John Penczek, Ingo Rothschohl	Johan Bergquist, Brian Berkeley, Sihui He, Edward Kelley, Andrew Watson
20	High Dynamic Range (HDR)	Florian Friedrich*	Timo Kunkel, Brian Berkeley, Neil Robinson, Sehyeok (Ted) Park, Karl Lang, Jeff Yurek, Chris Chinnock, Don Gyou Lee, Kenichiro Masaoka, Nandhu Nandhakumar
21	Color for Display Metrology	Kenichiro Masaoka*	Karl Lang, Brian Berkeley, Johan Bergquist, Youngshin Kwak
A	Metrology	Ed Kelley	
	12.6 Multicolor Pattern with Constant 25% APL	Karl Lang	
B33	HDR Ecosystem from the Metrology Viewpoint	Timo Kunkel	Florian Friedrich*, Brian Berkeley, Sehyeok (Ted) Park, Kenichiro Masaoka



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REVIEWERS: We would like to also thank everyone who volunteered to work on and review the document and who provided valuable feedback to the sub-committee chairs as well as to Paul and Ed. A list of contributors is given below but in case we missed anyone, we would like to thank everyone in advance for helping to edit and make suggestions for improving this document.

Adi Abileah, Luigi Albani, Zahir Alpaslan, Tim Anderson, Steve Atwood, Richard Austin, Otto Bader, Ye Seul Baek, Ryan Beams, Michael Becker, Johan Bergquist, Brian Berkeley, Nicholas Bevins, Rina Bhuva, Karlheinz Blankenbach, Ben Bodner, Ronan Boitard, Nicolas Bonnier, Paul Boynton, Michael Brill, Rick Brinkley, Kjell Brunnström, Andrew Bryant, Michiel Callens, Alexander Carpenter, Kai Chieh (Jay) Chang, Wei Chen, Chris Chinnock, Jongho Chong, Gavin Cook, Bill (Milo) Cummings, Scott Daly, Robert Donofrio, Allen Earman, John Ehmke, Steve Ellersick, Ronald Enstrom, Thomas Fink, Tom Fiske, Florian Friedrich, Tom Fuke, Eric Gemmer, Chad Greene, Jung Hyun Ham, Monirul Hasan, Sihui He, Rodney Heckaman, Alex Henzen, David Hermann, Dirk Hertel, David Hoffman, Hyung Ki Hong, Ericsson Huang, Jens Jørgen Jensen, Caleb Johnston, David Jung, Joe Kane, Kyung-Jin Kang, Yoojin Kang, Peter Karp, Ed Kelley, Louis Kerofsky, Bill Kilgallon, Choon-Woo Kim, Il Ho Kim, Jiman Kim, Youn Jin Kim, Udo Krüger, Timo Kunkel, Youngshin Kwak, Hyeok-Jun Kwon, Karl Lang, James Langehennig, Don Gyou Lee, Ernest Lee, Jongeseo Lee, Min-Jae Lee, Myong-Yong Lee, Shiu Pong Lee, Heinz Lemke, Xiaohua Li, Tom Lianza, Michael Linder, Max Lindfors, Yifan Liu, Dirk Maes, Kenichiro Masaoka, John Meehan, Mike Mignardi, John Miller, Carlos (Byungseok) Min, Erica Montbach, Tongsheng Mou, Jeff Mulligan, Shannon Mutschelknaus, Nandhu Nandhakumar, Jürgen Neumeier, Sonika Obheroi, Pavel Olchovik, Silviu Pala, Jason Park, SeHyeok (Ted) Park, Valeriano Ferreras Paz, John Penczek, Greg Pettitt, Andy (Bao-Jen) Pong, John Popoolapade, Bob Raikes, Linghui Rao, Neil Robinson, Ingo Rotscholl, Abhijit Sarkar, Dave Schnuelle, Prachi Sehgal, Roland Seibt, Sungwon Seo, Suchil Shah, Sikuan Shen, Marie Shoda, Euan Smith, Raymond Soneira, Dan (Dano) Steinhardt, Dale Stoltzka, Chih-Hsuan Sun, Shinichi Uehara, Rupal Varshneya, Zongkai (Cary) Wang, Phillip Warren, Andrew Watson, Mike Wilson, Martin Wolf, Gang Xu, Kirt Yanke, Jang-Jin Yoo, Jeff Yurek, Paul (Bo) Zhang, Xiangnan Zhu.

F1.3 ACKNOWLEDGMENTS VERSION 1.2

Top Level Acknowledgments: The entire committee would like to thank its chair, Michael Wilson (Westar Display Technologies) for taking the lead in getting this document completed. His tireless efforts have been extraordinary, in traveling all over the world to conduct meetings, in creating and maintaining the web presence of the ICDM (<https://www.sid.org/Standards/ICDM>), in motivating the committee members to contribute, in the late nights and weekends, and many other ways. This document would not exist without his leadership.

Ed Kelley, the previous editor, is greatly acknowledged for smoothly making the transition to the new editorship and for providing advice even after his retirement. Brian Berkeley is acknowledged for the scheduling, program management, and extensive reviews.

SID Acknowledgment: We would like to thank the Society for Information Display (SID) for bringing the ICDM committee into SID as part of the Definitions and Standards Committee and allowing us to develop this document to solve the needs of the display industry to create a single top-notch reference standard for how to measure and characterize displays. Thanks also to the SID Executive Committee for their help and support for business management issues to get the document released.

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11.10.2	Color Gamut Envelope for Reflective displays	Dirk Hertel	John Penczek*
21	Color for Display Metrology	Kenichiro Masaoka*	Peter Karp, John Meehan, John Penczek
A	12.7 Selectable Constant Average Picture Level	Dale Stoltzka	Johan Bergquist*
B17.3	PSF2BSDF	Michael Becker	John Penczek, Johan Bergquist*



REVIEWERS: We would like to also thank everyone who volunteered to work on and review the document and who provided valuable feedback to the sub-committee chairs as well as to Mike and Johan. A list of reviewers is given below but in case we missed anyone, we would like to thank everyone in advance for helping to edit and make suggestions for improving this document.

Richard Austin, Michael Becker, Johan Bergquist, Brian Berkeley, Thomas Fiske, SeHyeok Park, John Penczek, Robert Wanat, Michael Wilson



G. CHANGES & CORRELATIONS

Here we document changes in any new versions of this document. We also provide correlations with other standards documents (future).



G1 CHANGES & ADDITIONS IN CURRENT VERSION

Original document published on June 1, 2012, as version 1.03. This document is version 1.2 created May 23rd, 2023. Prior to this version we have made a few substantial corrections to a few sections as documented at <https://www.sid.org/Standards/ICDM#8271482-idms-changelog>:

Version 1.2 has the following changes:

Section	Title	Comment
1	Introduction	
1.2	Colorimetry, photometry, and radiometry	Corrected color terminology
2	Templates, Composite Metrics, and Suites	
2.1	Display description, identification and modes	Corrected color and grey scale terminology. Added palette and distinction between addressable and discernable colors. Modified Table 2.1.
2.2	Template for Emissive Displays	Added reference colour spaces, additivity condition to chromaticity area calculation. Corrected terminology. Removed u'v' area calculation. Modified Table 2.3
2.4	Vantage Point Measurements	Corrected terminology. Added luminance/chromaticity non-uniformity calculation, supplemental data, color selection, optimum viewing distance. Modified Tables 2.5, 2.6, 2.7
2.5	Luminance and Chromaticity Uniformity Template	Added calculations to Table 2.8, new Tables 2.9, 2.10, 2.11
2.6	Center Screen Basic Measurements Template	Added description, setup, procedure, analysis, and reporting. Modified Table 2.12
10	Temporal Measurements	
10.2	Response Time Metrics	Added note to 10.2
11	Reflection and Transmission	
11.7.3.2	Annulus Source Specular Reflection	New section
11.10.2	Color Gamut Envelope for Reflective Displays	New section
21	COLOR FOR DISPLAY METROLOGY	
21.2.1	Tristimulus Values and Standard Colorimetric Observer	Added CIE information. Figure 21.1 Illustration of 2-deg rule of thumb added
21.2.4	Uniform Color Spaces	Writing and logical flow improved/Gamut explicitly defined in D50 CIELAB space
21.3.4	Chromaticity Gamut Area	More detailed limitations of



		chromaticity gamut metrics provided
21.3.5	Relative Gamut Metrics	Writing improved with clarification the relationship between sRGB and Rec.709
21.4.2	Gamut Rings	Algorithm for gamut ring intersection added.
21.5	Light Measuring Device Considerations	New section

CHANGES

CHANGES



G2 CORRELATION WITH OTHER STANDARDS

For future versions as deemed necessary...

CHANGES

CHANGES



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H. BIBLIOGRAPHY

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- [6] Keller, Peter A. (1997). *Electronic Display Measurement: Concepts, Techniques, and Instrumentation*. New York: John Wiley & Sons. ISBN 0-471-14857-1. This book contains a great deal of valuable reference material, tutorial material, numerous references to the literature and existing standards, descriptions of how things work, standards organizations, where to get things, as well as measurement techniques.
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