

COLORS AND DISPLAY MEASUREMENTS

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Objectives

o Characterize color rendering for new monitor technologies (especially LCDs) as discussed in VESA committees and documents

- Conventional Profiling + more than full-screen + > 1 primary at a time**
- Quantify viewing-angle dependencies (color reversal)**
- Color-gamut metric**
- Verify colors from bits to light**

o Review venue: VESA Display Measurement Committee, VESA Color Working Group, IEC TC100 PC 61966)

o Caution: It's easy to have too many measurements (Brainard, Color Res. Appl. 1989)

1. Generalized Device Profiles.

Purpose: to quantify

- **single-primary profiles (not just gamma)**
- **inter-primary crosstalk,**
- **luminance loading.**
- **Tristimulus loading (new term)**

Measurements

- **Full-screen and small-box (.2 H x .2 W) test patterns**
- **Eight settings each of R, G, and B (in all 512 x 2 combinations)**

Venue

- **Video Electronics Standards Association Color Working Group (Todd Newman)**
- **Video Electronics Standards Association Display Measurement Committee (E. F. Kelley)**

2. LCD Color Reversal with Viewing Angle

Single-number metric of color that generalizes gray-level reversal to color reversal on LCDs. (VESA DMC Document May 1999)

Concept: Plot neighboring colors in chromaticity, to note whether the chromaticities (x,y) are ordered clockwise (CW) or counterclockwise (CCW) in (x,y) space. Vary direction of viewing until the ordering reverses.

Procedure:

(a) For gray levels n, define 3 neighboring colors by their (r, g, b) digital command values: reddish (n + 21, n, n), greenish (n, n + 21, n), and bluish (n, n, n + 21). Abut small patches of these three colors so they all meet at a single point on the screen.

(b) Measure CIE (x,y) values at a set of viewing angles: (x_r, y_r) for the reddish patch, (x_g, y_g) for the greenish patch, (x_b, y_b) for the bluish patch.

(c) Record CW or CCW ordering of colors in (x,y) proceeding from r → g → b .

Done **visually** (test pattern by E. Kelley, NIST), **graphically**, or by **computing**

$$P = (x_r - x_b)(y_g - y_b) - (x_g - x_b)(y_r - y_b) \quad (> 0 \text{ for clockwise ordering})$$

(d) Change viewing direction of the screen, find color reversal.

EXAMPLE OF CALCULATION

(From VESA DMC Document, May 1999)

Suppose

reddish patch chromaticity $(x_r, y_r) = (.34, .33)$

greenish patch chromaticity $(x_g, y_g) = (.33, .34)$

bluish patch chromaticity $(x_b, y_b) = (.33, .33)$.

Graphical presentation shows that the ordering of the chromaticities is clearly

CCW from $r \rightarrow g \rightarrow b$.

Algebraic confirmation: $P = 0.0001 > 0$.

3. Color Gamut Metric for Projector Systems

(VESA DMC Document, June 1999)

A gamut metric borrowed from the lighting industry (area in $u'v'$) quantifies color in projector systems (for which it is difficult to enforce a white point).

Why not a volume gamut? Volume depends on gains of primaries.

Why not measure saturation of primaries? Saturation depends white point.

Use Area of Primary Triangle in Uniform Chromaticity space (u',v')

--Chromaticities of primaries are stable

--Precedent for $u'v'$ in ISO, CIE, and ANSI standards

--Precedent for area metric in W. Thornton, Color Discrimination Index (JOSA 1972)

Divide by area inside spectrum locus (0.1952) to give absolute meaning.

Color Gamut Metric Procedure

(VESA DMC Document, June 1999)

If the measurement device measures CIE (x,y) values but not (u',v') values, then:

(a) Measure CIE (x,y) values for each primary at full-on (others off):
(x_r, y_r), (x_g, y_g), (x_b, y_b).

(b) Transform (x,y) pairs to the CIE 1976 (u', v'):

$$u' = 4x/(3 + 12y - 2x)$$
$$v' = 9y/(3 + 12y - 2x)$$

(c) Compute rgb triangle area in (u',v'), divide by 0.1952, multiply by 100 %:

$$A = 256.1 |(u'_r - u'_b)(v'_g - v'_b) - (u'_g - u'_b)(v'_r - v'_b)|.$$

If (u',v') are directly measured, skip to (c).

Color Gamut Metric Example Calculation

(VESA DMC Document, June 1999)

The following coordinates were measured on a particular projector:

Red: $u'_r = 0.443$, $v'_r = 0.529$
Green: $u'_g = 0.124$, $v'_g = 0.567$
Blue: $u'_b = 0.186$, $v'_b = 0.120$

Compute $A = 36$: Projector has access to 36 % area inside the spectrum locus.

References

1. Commission Internationale de l'Eclairage (CIE), Colorimetry (Second Edition), *Publication CIE 15.2*, Bureau Central de la CIE, 1986.
2. P. J. Alessi, *Color Res. Appl.* **19** (1994), 48-58.
3. ISO standards 9241-8 (color requirements for CRTs) and 13406-2 (measurement requirements for LCDs).
4. ANSI Electronic Projection Standards IT7.227 (Variable Resolution Projectors) and IT7.228 (Fixed Resolution Projectors).

4. Procedure to Verify Digital Color Systems

(NIST/VESA Display Forum 97, VESA FPDM Standard, May 1998 & SID Journal 1998)

- o Bits-to-light color verification**
- o Determines if color is conveyed correctly from one device to another**
- o Test for a Color Management System, but not itself a CMS**

PROBLEM

(NIST/VESA Display Forum 97)

Verify Degree of Success in Reproducing Colors on a New Device

--Want to Detect Digital Protocol Errors

--Don't Want to Confuse Digital Errors with Gamut Mismatch Errors

--Don't Want to Confuse Digital Errors with White-Point Mismatch Errors

APPROACH: ADAPTIVE COLOR TEST PATTERNS

(NIST/VESA Display Forum 97)

- Specify target colors that adapt to any VDU's white point**
- Specify digital inputs that make these colors on a standard VDU.**
- Feed test VDU with same inputs, & measure match of actual and target colors for that VDU.**

KEY CONCEPTS:

(NIST/VESA Display Forum 97)

- 9 Full-Screen Low-Chroma Colors**
- Target Tristimulus Values Match CRI Reflectances Under Model Light (Computed)**
- Model Light is Linear Combination of Daylight Eigenvectors that Matches Monitor White (Either Standard or Test)**

OFF-LINE PROCESSING
(NIST/VESA Display Forum 97)

Step 0. Compute tristimulus values (tsv's) of 9 reflectances as if lit by daylight-eigenvector spectra.

Inputs: -- 1931 CIE XYZ color-matching functions $x_j(\lambda_k)$
-- Daylight eigenvectors $S_0(\lambda_k)$, $S_1(\lambda_k)$, and $S_2(\lambda_k)$
-- First 8 CRI reflectances $r_i(\lambda_k)$

Outputs: 81 values.
-- 3x3 matrix A_{mj} (j'th tsv of m'th daylight):

$$A_{mj} = \sum_{k=1}^{31} S_m(\lambda_k) x_j(\lambda_k).$$

-- 3 x 3 x 8 array B_{mji} (j'th tsv of i'th CRI reflectance under m'th daylight):

$$B_{mji} = \sum_{k=1}^{31} r_i(\lambda_k) S_m(\lambda_k) x_j(\lambda_k).$$

PREPARE TEST COLORS FOR STANDARD VDU (NIST/VESA Display Forum 97)

Step 1. Select VDU & measure its white point X_{nR} .

Step 2. Compute target CIELUV values of CRI reflectances under model light.

-- Compute coeffs $(a_0, a_1, a_2) = \mathbf{a}$ for the l.c. of daylight eigenvectors:

$$\mathbf{a} = \mathbf{X}_{nR} \mathbf{A}^{-1}$$

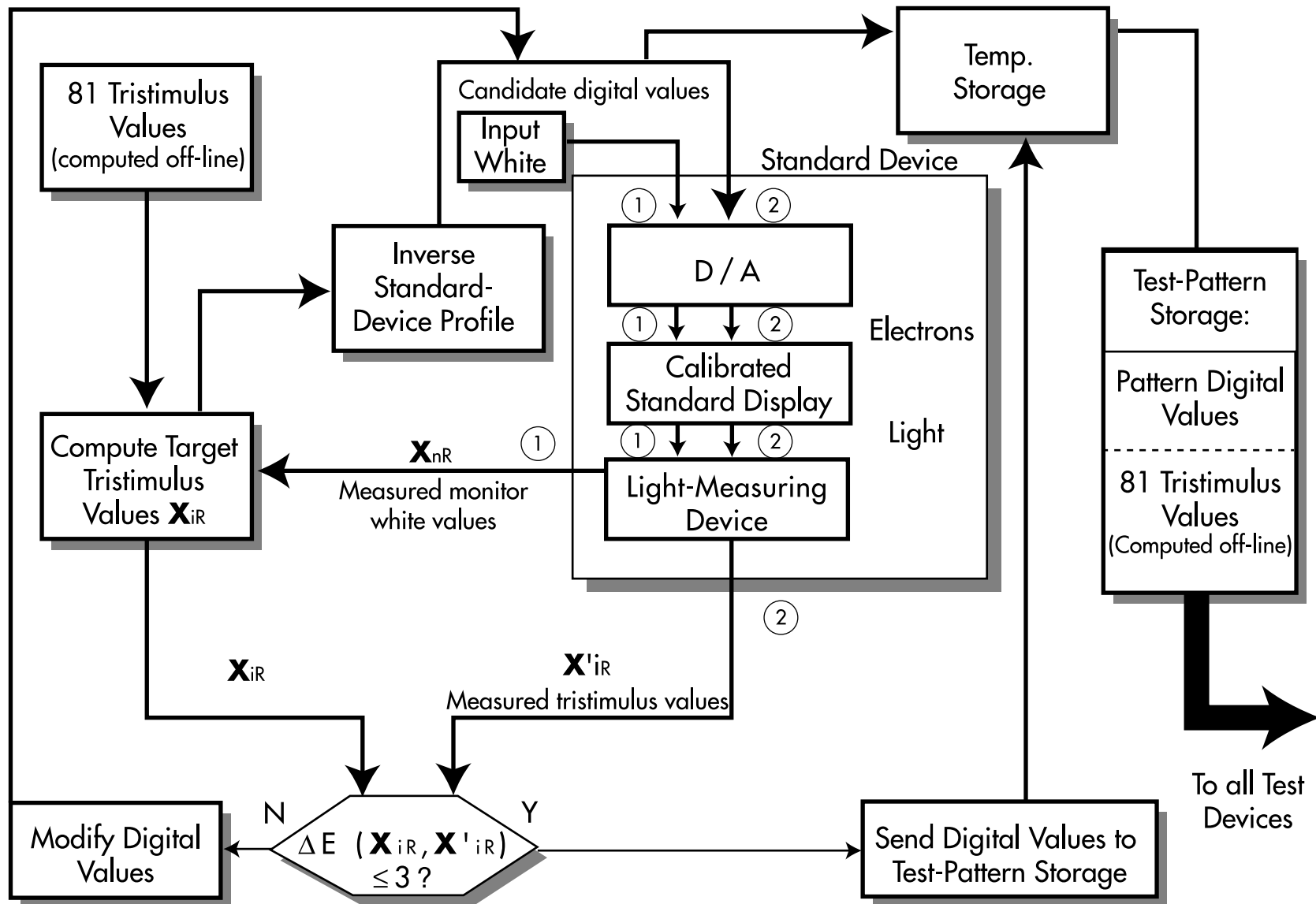
-- Compute 8 target CRI XYZ values:

$$(X_{iR}, Y_{iR}, Z_{iR}) = \sum_{m=0}^2 a_m (B_{m1i}, B_{m2i}, B_{m3i})$$

-- Convert to CIELUV using white point \mathbf{X}_{nR}

Step 3. Select digital colors so measured values match target. Use white point \mathbf{X}_{nR} .

Criterion: $\Delta E < 3$



(NIST/VESA Display Forum 97)

VERIFY COLORS ON TEST-VDU (NIST/VESA Display Forum 97)

Step 4. Measure test-VDU white point \mathbf{X}_{nT} .

Step 5. Compute target CIELUV values under model light.

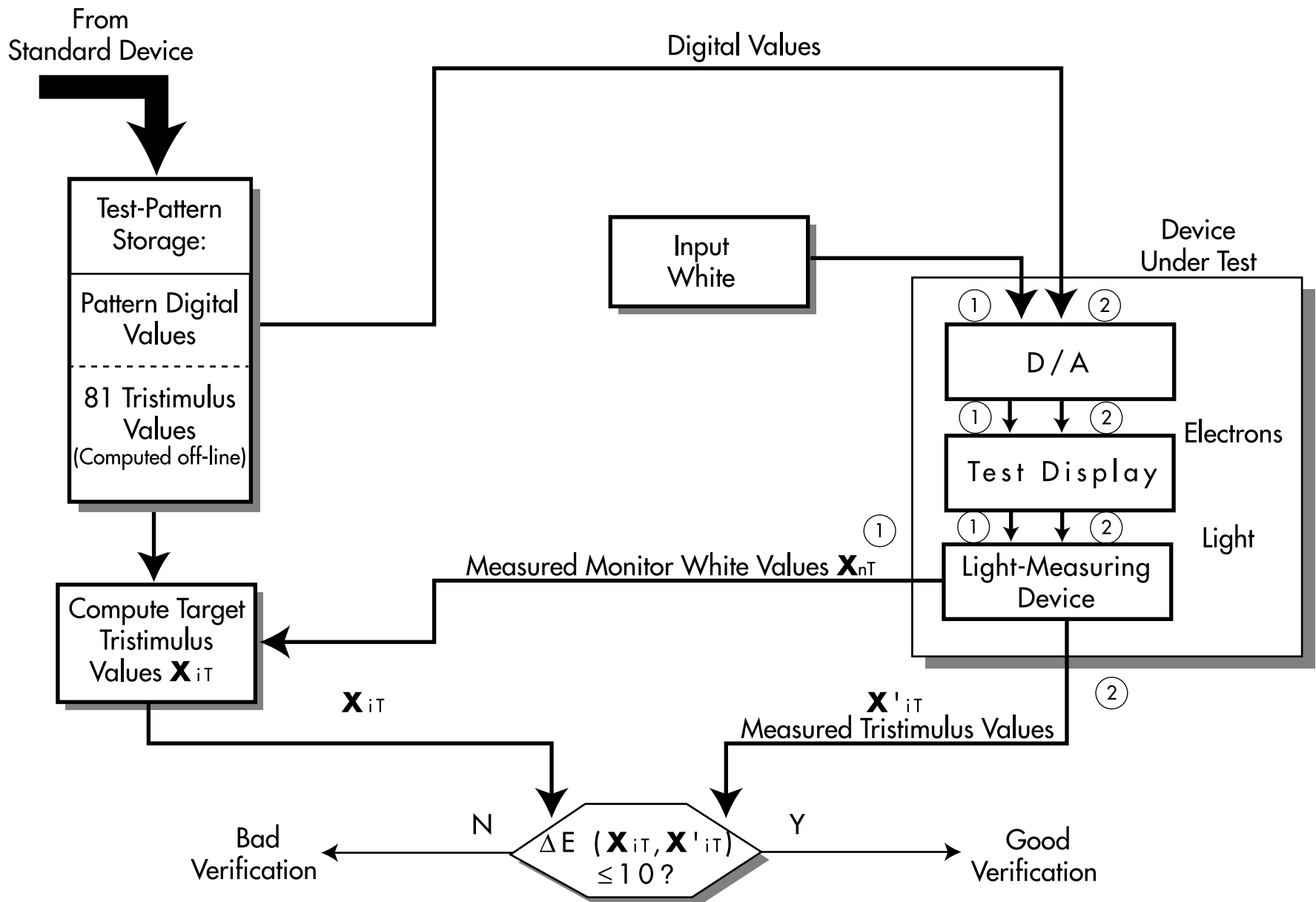
-- Compute coeffs \mathbf{b} for the l.c. of daylight eigenvectors that matches \mathbf{X}_{nT} : $\mathbf{b} = \mathbf{X}_{nT} \mathbf{A}^{-1}$

-- Compute target $\mathbf{X}_{iT} = \sum_{m=0}^2 b_m (B_{m1i}, B_{m2i}, B_{m3i})$

-- Convert to CIELUV using white point \mathbf{X}_{nT} .

Step 6. Drive test device with standard digital values, measure \mathbf{X}'_{iT} , & convert to CIELUV using white point \mathbf{X}_{nT} .

Step 7. Compute ΔE between target and measured colors.
Criterion $\Delta E < 10$.



(NIST/VESA Display Forum 97)

EXAMPLE OF USE (NIST/VESA Display Forum 97)

- Standard is a CRT; Test VDU is a laptop computer (LCD).
- 8-bit (R', G', B') drive both displays.
- No color-management system.
- For Std CRT, first digital estimate made with NTSC-based model.

CRI Color	COMPUTED		MEASURED			Display
	x	y	x	y	ΔE	
1	0.343	0.319	0.341	0.322	2.276	STANDARD Generator CRT
2	0.356	0.390	0.355	0.391	0.656	
3	0.348	0.465	0.348	0.464	0.145	
4	0.265	0.393	0.264	0.391	0.637	
5	0.238	0.293	0.238	0.292	0.558	
6	0.222	0.230	0.222	0.230	0.257	
7	0.258	0.226	0.259	0.227	0.628	
8	0.293	0.247	0.292	0.246	1.180	
1	0.374	0.349	0.334	0.352	68.68	TEST Laptop Computer LCD
2	0.382	0.413	0.367	0.335	34.42	
3	0.368	0.481	0.381	0.375	49.34	
4	0.285	0.422	0.345	0.441	29.74	
5	0.259	0.329	0.268	0.423	34.02	
6	0.242	0.265	0.227	0.299	25.95	
7	0.286	0.261	0.208	0.231	39.01	
8	0.326	0.281	0.267	0.245	33.56	

COMPARISON WITH PROPOSED SMPTE STANDARD

303M (NIST/VESA Display Forum 97)

- Both derive target tristimulus values using an illuminant-reflectance model.
- SMPTE pre-computes tristimulus values only for three white points (D65, D55, and 3100K). Our method accepts any white point.
- SMPTE uses 24 reflectances (including highly chromatic ones), not tuned to testing digital protocols.

Digital Verification: Conclusions

(NIST/VESA Display Forum 97)

- ΔE values are acceptably small for standard VDU, but not for test VDU.
- Further work will show if 10-unit criterion is realistic
- Method shows lots of room for improvement using color-management systems (CMS's)
- > This is a promising way to evaluate a CMS

OUTLOOK

- o More accurate profiles needed because of**

- New display technologies (LCD, Projection, etc.)**
 - More discriminating clientele**
- o More accurate profiles are possible because of**
 - More accurate equipment (spot photometers, etc.)**
 - Better computational facilities to use profiles**
- o Why has human vision forgiven our profiling errors?**