17.5: Projector Flux from Color Primaries

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Abstract

A standard methodology exists for estimating the flux from front projection displays by sampling the projected illuminance of a white source signal. With the advent and use of white projection primaries, a dramatic increase in flux can be achieved over the combination of red, green, and blue primaries alone. However, saturated-color areas in an image are constrained to low flux levels relative to the display maximum and further undergo a perceptual compression in relative lightness when a white primary is used. As a result, bright saturated colors cannot be rendered accurately and the appearance of full-color imagery is distorted. Due to these problems, the display of color-accurate imagery does not generally use the white primary. We verify a measurement method that fills the need for providing an equivalent flux measurement that will better describe the performance of all RGB and RGBW projectors when they render full-color imagery.

1. Introduction

It has been observed that digital projection-display devices that include a white (W) image field or white sub-pixels in addition to the "standard" set of R (red), G (green) and B (blue) primaries can reduce the effective perceptual color gamut of projected information. [1, 2] This reduction is manifest by intended bright, saturated colors being constrained to low flux values, both absolutely and relative to the maximum white of the display. In such RGBW displays, the white "primary" darkens bright colors in two ways: (1) Relative to RGB displays, the illuminance of pure R, G, or B is low because the white primary must share the screen area or active projection time even when it is shut off, and (2) The visual system tends to adapt to the prevailing light so that perceived white stays the same; hence a high-illuminance white will depress the perceived brightness of other colors. To see adaptation working in the reverse direction, one can make bright, saturated colors look even brighter and more saturated by artificially depressing the white in a scene. [3] Such variations in the effective perceptual color gamut of imaging devices such as projection displays may be readily characterized via perceptual experiments with human observers and can be estimated by the use of three-dimensional color spaces such as CIELAB or color appearance models such as CIECAM02. [4, 5] However, rather than address the subtleties of visual adaptation and its effects on perceived color, we choose a metric for RGBW displays that is based on simple optics, namely the sum of the fluxes of the full-on pure primaries R, G, and B.

Whereas the color gamut reductions described above may not be important for the presentation of simple text and some graphics, a reduction in the perceptual color gamut can be highly objectionable when imagery is viewed. Thus, we consider here two modes of projector operation: a **text/graphics mode** and an **imagery mode**. The text/graphics mode can use a white primary component in addition to the RGB primaries. The imagery mode will use only the RGB primaries without any contribution from the white primary. We limit our discussion to front projectors that are intended to use standardized RGB signals such as the sRGB specification. [6] (Any future use of the white primary to enhance only certain highlights in an otherwise normal scene is not considered here as well.) We want to be able to characterize the projected luminous flux of any projector in both modes.

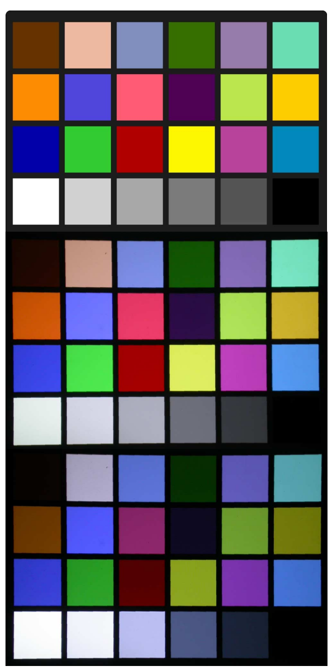

Figure 1. Color rendering with and without a white primary.

Figure 1 shows an example of a test pattern based upon the Macbeth ColorChecker® [7] that depicts the difference between the text/graphics mode and imagery mode in a projector that includes a white primary component. The top image is the original digital image sent to the projector. The middle image is a photograph of the screen with the projector in the imagery (RGB) mode, and the bottom image is a photograph of the screen with the projector in the text/graphics mode including a white primary component (RGBW). You will note that the introduction of the white primary tends to provoke a relative darkening of the colors compared to the white level along with shifts in the perceived hue and color saturation. These photographs can provide only approximations to how the projected images actually look, but they

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convey a reasonable impression of how the white primary influences imagery.

To characterize the effective light output of digital projectors to be used for the accurate rendering of color imagery, and to compare the color-balanced performance modes of RGB projectors with those employing an additional white primary component, a method has been proposed in the literature by one of the authors that employs a nonatile (nine-tile) trisequence of RGB blocks—see Figure 2. [8] This method, which is intended to avoid the contributions from any white primary components, is compared with the full-white-screen method outlined in the existing measurement standards for fixed-resolution projectors. [9] Rather than our measuring a white screen, this method measures the three tiled patterns and combines the results to provide a flux estimate based only upon the RGB primaries without a white primary contribution. The nonatile trisequence patterns are referred to by their diagonal color: NTSR has a red diagonal, NTSG has a green diagonal, and NTSB has a blue diagonal. The use of the tiled patterns containing blocks of all three primaries rather than three simpler full-screen primary patterns is to help avoid any addition of a white primary (the number of measurements that would be made is the same if we use the tiled patterns or the full-screen patterns).

2. Theory

We will employ the correct terminology "flux," whereas the projection industry and existing or proposed standards use the coined term "light output" for measurements of the white screen and "color output" for measurements of the flux that use the nonatile trisequence patterns (Figure 2), where any white primary component and other complications are avoided.

In part, the method employed to measure the flux is based upon an existing standard. [9] That standard calls for a sampled measurement of the illuminance $E_{\mathrm{W}ij}$ of a projected white image in nine places at the center of rectangles that divides the full screen approximately (±2 px) into a 3 × 3 matrix of equally sized rectangles. The estimated flux of the white screen Φ_{W} is the product of the average illuminance and the measured area A of the image;

$$\Phi_{\mathrm{W}} = \frac{A}{9} \sum_{i,j=1}^{3} E_{\mathrm{W}ij} \; . \tag{1}$$

All the measurements made for this document confined the position accuracy to within 2 % or less of the centers of the 3 × 3 rectangles.

The area A is the area of the projected image on the projection screen (a plane in space and not an actual screen was used for all the measurements made for this document). Because it is difficult to position the projected area exactly onto a specific size of screen, we must account for the actual projected size of the image. Given a general planar convex quadrilateral where the diagonals are specified by vectors **p** and **q**—see Figure 3—the area is given by half the magnitude of the cross product of the diagonal vectors: [10]

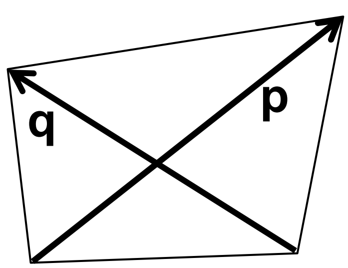

Figure 3. Area of projected image.

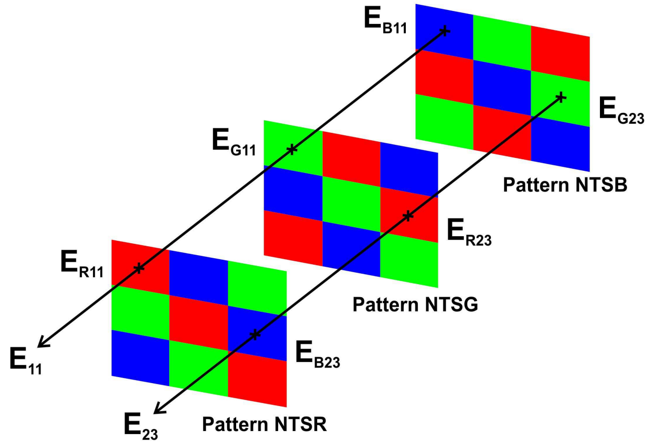

Figure 2. Nonatile trisequence patterns.

$$\begin{aligned} A &= \frac{1}{2}\left|\mathbf{p}\times\mathbf{q}\right| = \frac{1}{2}\left\| \begin{matrix} \mathbf{e}_{\mathrm{x}} & \mathbf{e}_{\mathrm{y}} & \mathbf{e}_{\mathrm{z}} \\ p_{\mathrm{x}} & p_{\mathrm{y}} & p_{\mathrm{z}} \\ q_{\mathrm{x}} & q_{\mathrm{y}} & q_{\mathrm{z}} \end{matrix} \right\| \\ &= \frac{1}{2}\Big|(p_{\mathrm{y}}q_{\mathrm{z}} - p_{\mathrm{z}}q_{\mathrm{y}})\mathbf{e}_{\mathrm{x}} \\ &\quad -(p_{\mathrm{x}}q_{\mathrm{z}} - p_{\mathrm{z}}q_{\mathrm{x}})\mathbf{e}_{\mathrm{y}} \\ &\quad +(p_{\mathrm{x}}q_{\mathrm{y}} - p_{\mathrm{y}}q_{\mathrm{x}})\mathbf{e}_{\mathrm{z}}\Big| \end{aligned} \; . \tag{2}$$

We assume that the measurement plane is the x–y plane so that all components in the z–direction are zero. This reduces to

$$A = \frac{1}{2}\left|\mathbf{p}\times\mathbf{q}\right| = \frac{1}{2}\left|(p_{\mathrm{x}}q_{\mathrm{y}} - p_{\mathrm{y}}q_{\mathrm{x}})\right| , \tag{3}$$

where x is the horizontal position (positive to the right) and y is the vertical position (positive up) with the origin at the bottom left of the measurement plane defining the imaginary screen in our case. To establish a simple estimation of the uncertainty in the area measurement, define a square with the same area as this distorted rectangle $A = s^2$. Given that each side has the same uncertainty δs in its measurement, to a good approximation the relative uncertainty of the area measurement is

$$\delta A / A = \sqrt{2}\, \delta s / s \; . \tag{4}$$

At the time the original standards were written and adopted with revisions by other standards organizations, white primaries (or, in fact, any additional primaries used in combination with R, G and B) were not commonly present in projection systems. Because of the different modes that can include the contributions of a white primary, we make the distinction between the projector flux Φ_{W} with a possible white primary included and the projector flux Φ_{RGB} that includes no white primary.

For measurements using three nonatiling trisequence patterns, the equivalent illuminance E_{ij} for any location i, j is a combination of the illuminances from each pattern at that location (see Figure 2):

$$E_{ij} = E_{\mathrm{R}ij} + E_{\mathrm{G}ij} + E_{\mathrm{B}ij} \ . \qquad (5)$$

The estimation of the flux Φ_{RGB} is obtained by multiplying the average equivalent illuminance for the nine locations by the projected area:

$$\Phi_{\mathrm{RGB}} = \frac{A}{9}\sum_{i,j=1}^{3} E_{ij} = \frac{A}{9}\sum_{i,j=1}^{3}(E_{\mathrm{R}ij} + E_{\mathrm{G}ij} + E_{\mathrm{B}ij}) \ . \qquad (6)$$

The flux Φ_{RGB} should include no contribution from a white primary. For measurements using the white screen, the flux Φ_{W},

$$\Phi_{\mathrm{W}} = \frac{A}{9}\sum_{i,j=1}^{3} E_{\mathrm{W}ij} \ , \qquad (7)$$

may include contributions from a white primary, depending upon the mode of the projector.

Table 1. Luminous flux Φ based upon sampled illuminance measurements.

Front Projector	White Primary Available? (Y/N)	Φ_{W} White Screen (lm)	Φ_{RGB} RGB Nonatiling Trisequence (lm)	RGB Color Contribution to Flux (%)	White Primary Contribution to Flux (%)
A	Y	1471	464	32%	68%
B	N	1063	1067	100%	NA
C	Y	1894	578	31%	69%
D	Y	1937	588	30%	70%
E	N	2027	2060	100%	NA

NA = not applicable

3. Apparatus and Measurement Results

The chosen size of the projected image is 1.2 m × 0.9 m, having an aspect ratio of 4:3. The area is approximately $A = 1.08\ \mathrm{m}^2$. A metal framework outlines the intended image area with black felt behind and above the framework in order to reduce contamination from scattered light. The projector rests on rails that are orthogonal to the image plane and at the bottom of the framework. In the corners of the framework are millimeter arrays that permit the accurate measurement of the projected image.

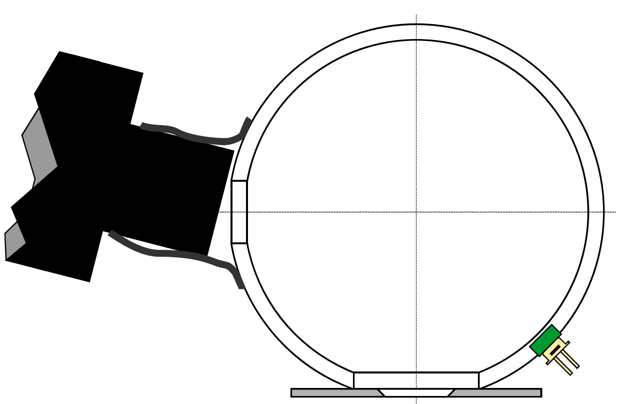

Figure 4. Spectroradiometer and integrating sphere.

A spectroradiometer views the front interior wall of an integrating sphere of 150 mm diameter. The wall of the sphere is made of sintered-powdered polytetrafluoroethylene with a photopic photodiode embedded in the front wall of the sphere—see Figure 4. The lens is wrapped with black felt to seal the measurement port from stray light. The spectroradiometer-integrating-sphere assembly is moved to the nine points by a positioning system.

Five front projectors were measured; three included a white primary and two did not—see Table 1. The projectors not containing a white primary measured approximately the same for a white screen as for the nonatiling trisequence. The projectors containing a white primary showed dramatic increases in flux from the nonatiling trisequence to the white screen, as much as a 70 % flux increase.

Table 2. Relative uncertainty evaluation.

1	Cosine correction contribution (u_{cc}, no correction made for this)	Type B	0.38 %
2	Calibration of spectroradiometer (u_{sr})	Type B	2.0 %
3	Deviation between the luminance meter (to calibrate the photodiode) and spectroradiometer (u_{dev})	Type B	1.9 %
4	Scattered light contribution average of all nine measurement locations (u_{sl}, no correction made for this)	Type B	0.13 %
5	Contribution from calibration of photopic photodiode monitor used as a calibration lamp monitor (u_{m})	Type A	0.23 %
6	Repeatability in illuminance inference from wall luminance measurements that use the spectroradiometer and 150 mm diameter integrating sphere (u_{d})	Type A	0.47 %
7	Source area relative uncertainty contribution ($\delta A_{\mathrm{s}}/A_{\mathrm{s}}$)	Type A	0.23 %
8	Calibration geometrical component relative uncertainty—source and detector distances and radii (u_{geo})	Type A	0.28 %
9	Projection area measurement relative uncertainty ($\delta A/A$)	Type A	0.82 %
	Relative combined standard uncertainty:		**3 %**
	Relative expanded uncertainty with a coverage factor of two:		**6 %**

3.1. Measurement Uncertainty

The expanded relative uncertainty with a coverage factor of two is estimated to be 6 % for these flux measurements—see Table 2 for a list of the component uncertainties (numbered items). [11] (In the case of random variables, the component uncertainties represent a single standard deviation.) The combined standard uncertainty is the root-sum-of-squares of the component uncertainties, and the expanded uncertainty is the coverage factor times the combined standard uncertainty. A number of the component uncertainties could have been corrected and eliminated. However, because their contributions were small, we chose not to do so and added them into the overall uncertainty—see items one and four.

As an example of the estimation of an uncertainty, the uncertainty in the framework defining the area is estimated to be 2 mm. We estimate the uncertainty in the horizontal or vertical measurement of the projected image to be 6 mm to account for any imprecision in the sharpness of the focus of the projected image at the edges as well as accuracy in measurement of the placement of the image. Referring to Eq. (4), $s = 1.039$ m, and we will take $\delta s = 6$ mm. The resulting relative component uncertainty in the area of the projected image is estimated to be $\delta A/A = 0.82$ %. Full details of this measurement process and uncertainty analysis are available in a NIST internal report. [12]

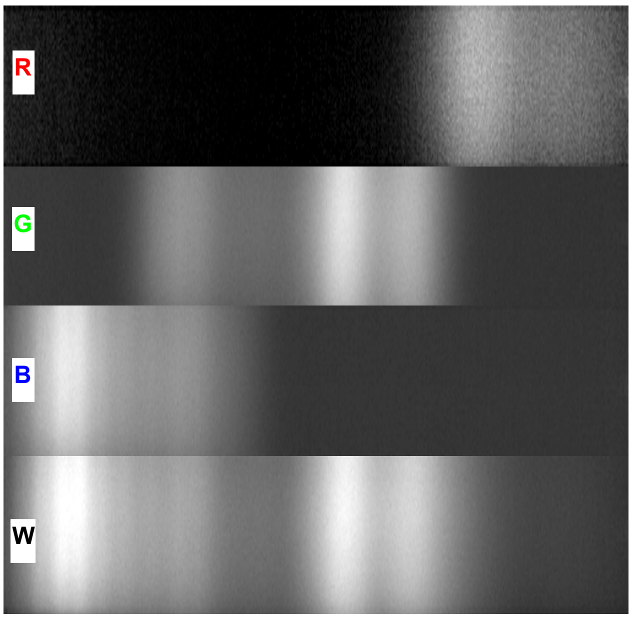

Figure 5. High-speed, low-resolution spectrometer results.

3.2. Determination of Compositions of White and Primaries

To prove whether or to what extent a white primary is present, a high-speed, low-resolution spectrometer was developed to determine how each projector renders a white or primary-color screen in each mode of operation. In order to be sure that a certain projection mode does not add in a white primary component, the spectra of the white screen can be monitored in time. A collimated detector consists of a short-focal-length lens with a polished end of a 2 mm diameter plastic fiber-optic cable with black protective sheath placed at its focal point. The cable is routed to the spectrometer. The end of the cable at the spectrometer is elongated vertically and narrowed horizontally. A lens collimates the output of the cable into a diffraction grating, and another larger lens focuses the spectral image onto the detector array of the high-speed camera. Figure 5 shows the results from the high-speed spectrometer when a white screen is measured within one frame. Violet is on the left, red on the right. The red spectrum has been enhanced to make it more visible.

4. References

[1] D. R. Wyble and M. R. Rosen, "Color management of DLP projectors," IS&T/SID 12th Color Imaging Conference, 228–232 (2004).

[2] R. L. Heckaman and M. D. Fairchild, "Effect of DLP projector white channel on perceptual gamut," Journal of the SID, Vol. 14, No. 9, pp. 755-761, (2006).

[3] R. L. Heckaman and M. D. Fairchild, "Expanding Display Color Gamut Beyond the Spectrum Locus," Color Research & Application, Vol. 31, No. 6, pp. 475-482, (2006).

[4] M. D. Fairchild, "Color Appearance Models, 2nd Edition," West Sussex, England: John Wiley & Sons Ltd, (2005).

[5] CIE Technical Report 159 (2004): A colour appearance model for colour management systems: CIECAM02. Note that CIE is Commission Internationale de l'Eclairage (International Commission on Illumination).

[6] IEC 61966-2-1 Ed. 1.0, Multimedia systems and equipment - Colour measurement and management - Part 2-1: Colour management - Default RGB colour space – sRGB. IEC is International Electrotechnical Commission.

[7] Any commercial item referred to in this paper or presented in a photograph is identified only for the purpose of complete technical description. Such a reference does not imply recommendation or endorsement by the National Institute of Standards and Technology neither does it necessarily suggest suitability to task.

[8] K. Lang, "Analysis of the proposed IEC 'Color Illuminance' digital projector specification metric, using CIELAB gamut volume," Late-Breaking-News Paper Presented at the 15th IS&T/SID Color Imaging Conference, Albuquerque, NM, November 2007.

[9] *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.

[10] http://mathworld.wolfram.com/Quadrilateral.html

[11] For a discussion of the proper way to specify uncertainty see: B. N. Taylor and C. E. Kuyatt, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Technical Note 1297, 1994 Edition.

[12] E. F. Kelley, K. Lang, L. D. Silverstein, and M. H. Brill, "A Rational Methodology for Estimating the Luminous Flux Based upon Color Primaries from Digital Projection Displays," NISTIR 6657, 29 pp. , January 2009.