

Light measuring device diagnostics for the photometric and colorimetric measurement of flying-spot displays

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ABSTRACT

Flying-spot displays use narrow-spectrum high-power sources that scan the image across the display screen. They can provide a bright display with a large color gamut. When such displays are measured with conventional light-measuring devices (LMDs) such as luminance or illuminance meters, there is concern that the LMD may not accurately measure the display's photometric and colorimetric output. The unique characteristics of the source may exceed the limitations of the instrumentation. A series of diagnostics has been developed that allows for an evaluation of LMDs for use in measuring flying-spot displays. Limitations resulting from LMD saturation, timing, and tristimulus or photopic filters can be revealed, and in some cases, specific causes can be identified. Each diagnostic will be demonstrated using several instruments, including luminance meters, illuminance meters, colorimeters and spectroradiometers. Using a simple comparison box, flying-spot displays can be viewed side-by-side with steady-state sources in a bipartite image. After the sources have been visually matched in color and luminance, the two images can be measured (light output and color) with a particular LMD, and results compared. Any significant difference between results would indicate a limitation of the LMD. Further diagnostics, using integrating spheres, neutral density filters and interference filters, are used to aid in identifying the nature of the limitation, and in some cases, point to solutions.

Keywords: Display measurement, measurement diagnostic, flying-spot displays, laser displays, light-measuring devices, color measurement

1. INTRODUCTION

Many different light-measuring devices exist, employing different designs and technologies, for use in display metrology. These include a wide variety of luminance meters, illuminance meters, colorimeters, and spectroradiometers, and are usually selected as a function of measurement application, price, and performance specifications. Such instruments are often chosen carefully and thoughtfully by the user, and typically provide the intended information. However, LMDs only approximate the response of the eye (to varying degrees of success), and thus may suffer limitations under certain conditions. Often the user can compensate for these limitations via inexpensive techniques or chose to employ the instrument restrictively. However, diagnostics must first be used to determine whether constraining conditions exist.

1.1 Narrow-Width, High-Energy Pulses

The unique characteristics of flying-spot displays, namely the scanning of a narrow-band high-power beam to inscribe an image onto a display screen, can cause LMDs to provide incorrect measurement data. In order for the projected image to provide adequate light output at each point on the screen, a high-powered energy beam (such as a laser) must quickly traverse the entire image field within one frame interval. For example, assume you want to project a 2 m^2 , 1024×768 pixel image at 1500 lumens. Let the refresh rate of the image be 60 Hz so that the time to write the complete image $\Delta t = 1/(60\text{ Hz}) = 16.7\text{ ms}$. For such a configuration, it would take $\delta t = 21.2\text{ ns}$ to "write" a single pixel on the screen. From the point of view of the LMD, this would be a 21 ns pulse. The average

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illuminance of the image would be $E_a = \Phi_{\text{total}} A_{\text{total}} = 750 \text{ lx}$. Thus the peak illuminance of this narrow pulse would be $E_{\text{peak}} = E_a \times (\Delta t / \delta t) = 5.90 \times 10^8 \text{ lx}$. Can the LMD correctly measure such a display, or will the large peak illuminance saturate the LMD? This can be easily determined using simple diagnostic techniques.

1.2 Saturated Sources

For display that utilize saturated-color sources (such as lasers or narrow-band LEDs) to provide the illumination, observers notice that when generating a monochromatic color on the screen, the perceived brightness increases with chroma while the luminance remains constant. This physiological phenomenon, often referred to as the Helmholtz-Kohlrausch effect [for example, see 1, 2, 3], is found to be true for all colors except yellow. Some observers notice that when comparing a white field generated by a combination of three saturated monochromatic sources to a white field generated by a heterochromatic broadband source, the saturated-source white may appear brighter when the luminances of both fields are the same. In other words, the brightness-to-luminance ratio appears not to be univariate for white fields of similar chromaticity but differing spectral distribution. Is this a perception phenomenon or an instrumentation problem?

We suggest that in some cases the perceptual differences may actually be LMD inaccuracies. When the spectral power distributions of different light sources are compared, errors may result due to the imperfect matching of the photopic filter to the $V(\lambda)$ curve, or in the case of tristimulus colorimeters, the $\bar{Y}(\lambda)$ filter to the color matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$. Spectroradiometers may have trouble because of background subtraction errors [4]. Once again, simple diagnostics may be used to evaluate the particular LMD.

2. DIAGNOSTICS

2.1 Comparator Box

To determine whether the unique characteristics of flying-spot displays can confound traditional LMDs, we compare such displays to a conventional display using a diagnostic comparator box [5] (Fig. 1). This box, manufactured with black plastic material, rests upon a 25 cm $\times$ 15 cm black-anodized breadboard with tapped holes. Three 50 mm diameter holes are cut in the plastic at the positions shown in Figs. 1 and 2; two are entrance ports into which the projectors are imaged, and one is for viewing. White reflective material or mirrors are mounted onto rods and secured into the tapped holes such that a bipartite image can be discerned at the viewing port (Fig. 2).

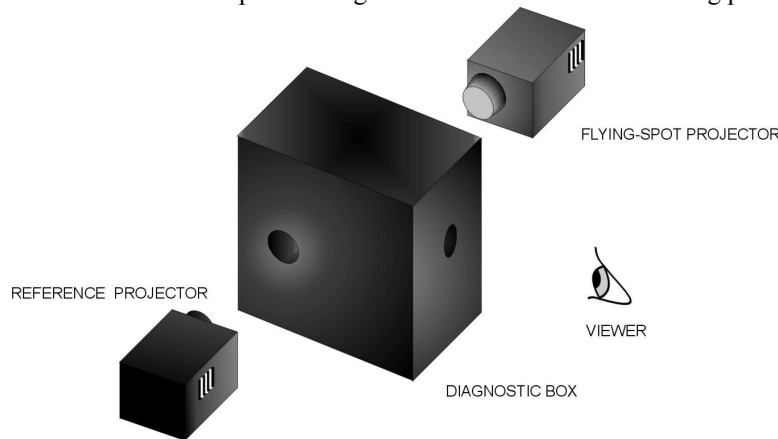


Figure 1. Comparator box.

As shown in Figs. 1 and 2, each display is projected into the comparator box onto a white sample. These samples are aligned such that an observer may view a bipartite image of both displays through the viewing port, the image split in half vertically by a knife-edge border. For a direct-view display the white sample should be replaced with a flat mirror. If two direct-view displays are being compared, verify that the distances from each source to its corresponding mirror are identical to ensure that the viewer may focus on both images simultaneously.

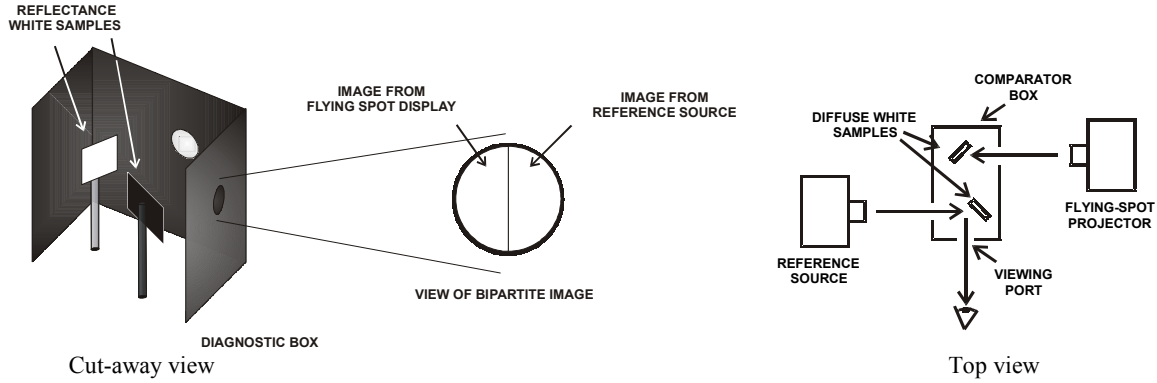


Figure 2. Bipartite image.

The procedure is relatively simple, based on an established standard methodology that was developed early in photometry. The viewer adjusts the two sources to match in both perceived brightness and chromaticity (preferably using a white field image) by obtaining a minimally distinct border between each half of the image. Position the sources and samples (or mirrors) so that a homogeneous circle is viewed when both halves are matched. Then the desired quantity (luminance, illuminance, chromaticity or spectral distribution) of each half of the bipartite image may be measured through the viewing port. A mask may be required to avoid stray light corruption [6]. To measure the illuminance, the top of the comparator box is designed with access holes into which illuminance meters can be lowered. The white samples must be carefully removed and then the meters placed in the same orientation. In this case, the projectors must be far enough away from the meters to reduce any $1/r^2$ dependencies, where r is the distance of the source from the image.

If the measured light output of both images are within acceptable limits of each other (these limits depend on the user's requirements), then the LMD clearly does not suffer from any of the aforementioned disfunctionalities, within these limits. If not, we suggest further evaluation, described below. Similar reasoning can be applied to the chromaticity measurements. Perform these diagnostics for a range of light outputs and color temperatures to provide a thorough characterization. Be aware that this diagnostic does not substitute for a calibration of the device, but rather serves as a method for evaluating the performance of the LMD under specific conditions.

2.2 Flux Saturation

2.2.1 Comparison method. Perform the procedure described in section 2.1. If the light-output readings do not match, then use a set of neutral density (ND) filters between the source and the LMD (see Fig. 3). We recommend the metal-evaporated type to minimize wavelength dependence. Be sure the ND filters do not have any pinholes. The optical density of these ND filters can be determined using the conventional light source. The transmission should measure equivalently for the flying-spot source. If both readings provide the same transmission

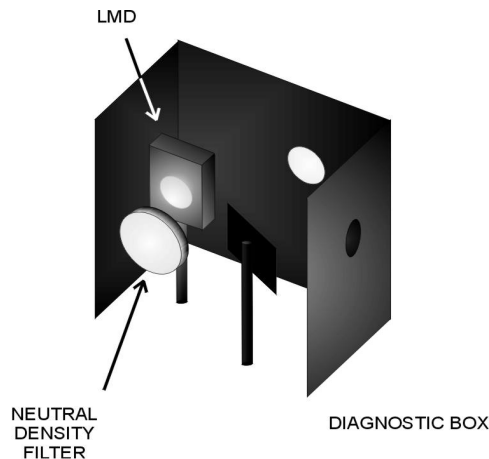


Figure 3. Saturation test using a neutral density filter.

determination, then consider a possible integration error or spectral mismatch problem (see section 2.3). If the transmission measurements are different, then the instrument is most likely saturating. Initial tests indicated that this was a valid diagnostic for indicating possible saturation [7]. Bear in mind that for all of the methodologies discussed, the obtained saturation level is only valid for the particular configuration and the characteristics of the particular display “pulse.”

2.2.2 Varying-distance method. Additional methods may be employed to further characterize the LMD and determine at what level it saturates, hopefully leading to adequate identification of the specific cause of the saturation effect. One such method calls for varying the distance of the detector from the LMD to determine at what level and settings the instrument saturates (see Fig. 4). For illuminance meters, the unit is placed in the image plane. For luminance meters, a white sample is placed in the image plane. To compare luminance readings with illuminance data, the white sample should be calibrated for the luminance factor β at this configuration, so that illuminance data can be calculated from the relationship:

$$E = L \frac{\pi}{\beta} . \quad (1)$$

Alignment must be carefully established so that in each configuration, the instrument is normal to the source, and that each configuration is reproducible. Take care to avoid stray light contamination from reflections off of walls, equipment, observers and other objects in the room.

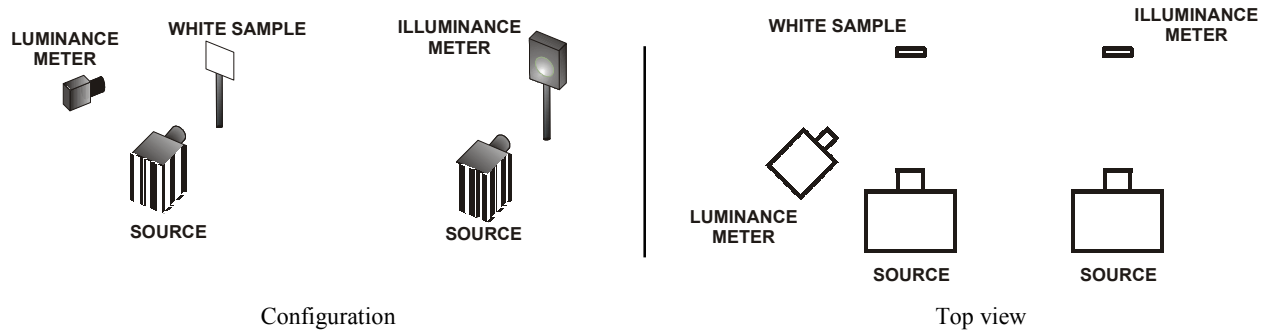


Figure 4. Varying-distance method for evaluating saturation of LMDs.

2.2.3 Integrating sphere method. Alternatively, an integrating sphere may be used. Figure 5 shows a three-port sphere: one port for the display source, one for the LMD, and the third for a photodiode monitor. Varying the lamp distance provides adjustment of the illumination of the sphere. Illuminance meters are placed so that the edge of the measurement head is aligned with the plane of the exit port. For luminance meters, the device should be placed at an appropriate distance and adjusted so that the lens is focused on the exit port (not the back wall of the sphere).

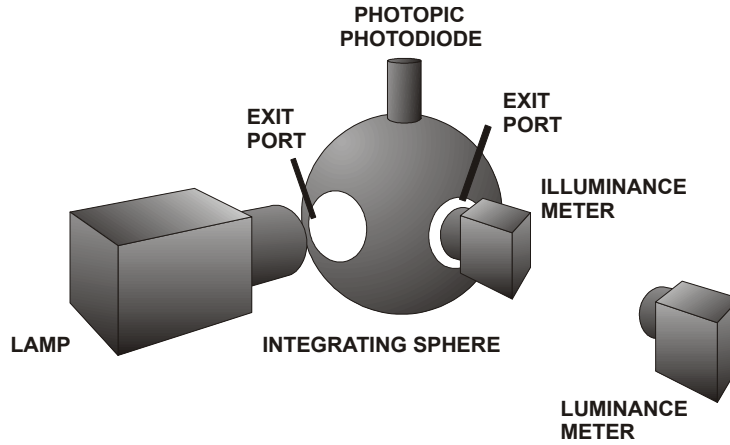


Figure 5. Using an integrating sphere to evaluate LMD saturation.

The sphere need not be calibrated, but should be coated with a high-reflectance material such as barium sulfate. An uncoated, closed-cell polystyrene box has been demonstrated to be a rugged and inexpensive alternative for situations that don't demand the requirements of a carefully constructed sphere [8], and may be applicable for this method. However, more work is needed to verify its performance in this particular diagnostic.

A photopic photodiode is used to monitor any changes in the sphere illumination resulting from alignment of the LMD. Perturbations at the exit port can cause changes in the sphere illumination. Careful adjustments of the LMD alignment can be made to ensure that photodiode output current remains constant when substituting different LMDs for comparison or when repeating measurements with a single instrument. The photodiode current should remain constant within the desired uncertainty.

2.3 Color Saturation

The comparator box may also be utilized for evaluating errors that result from spectral differences of sources of similar chromaticity and luminance. Generate a white field with both displays, matching the flying-spot display to the reference source for perceived luminance and color. Measure the light output and chromaticity for each half of the bipartite image. If the data from both images compare within user acceptable limits, then the LMD does not suffer from any significant color measurement problem

For further evaluation, use the measure each single narrowband source separately. Because the total luminous power of the source is the sum of the luminous power of each wavelength, the light output should combine additively, e. g.,

$$L_T = L_R + L_G + L_B, \quad (2)$$

where L_T is the total source luminance, and L_R , L_G , and L_B are the respective narrowband sources that combine to produce the narrow-band spectra source. Alternatively, additive tristimulus values (X , Y , Z) would indicate accurate color measurement, i. e.,

$$\begin{aligned} X_T &= X_R + X_G + X_B, \\ Y_T &= Y_R + Y_G + Y_B, \\ Z_T &= Z_R + Z_G + Z_B. \end{aligned} \quad (3)$$

Also, placement of the chromaticity coordinates of each narrowband source on the International Commission on Illumination (CIE) 1931 color chart can provide information for analysis of error. How far off the measured chromaticity of the saturated source deviates from the spectrum locus can indicate possible sources of error (see Figs. 6 and 7). Internal scattering, stray light, background subtraction or mismatched LMD filters can be attributed to the cause [4].

3. RESULTS

3.1 Instrumentation

We investigated the performance of several LMDs (see Table 1) using the diagnostic procedures outlined above. These include four illuminance meters (two single-detector with cosine diffuser models, one photopically corrected silicone photodiode with an opal glass diffuser and one diode-array spectroradiometer mounted with a cosine diffuser), a luminance meter, a colorimeter and a diode array spectroradiometer. The photopic photodiode produces a current with a calibrated lux-to-current ratio that is measured by a digital multimeter (DMM) and was linear over the range of interest.

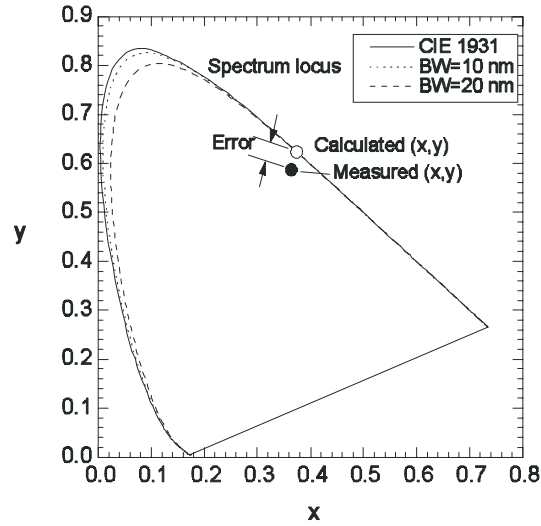


Figure 6. Using CIE 1931 chromaticity diagram to evaluate color accuracy.

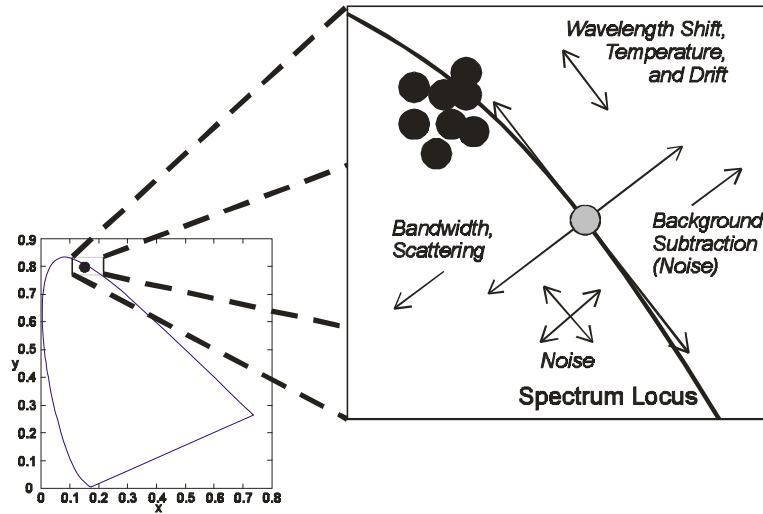


Figure 7. Possible errors in saturated color measurements.

Table 1. Instruments Evaluated With Diagnostics

Designation	Quantity measured	Description
Instrument #1	E	illuminance meter
Instrument #2	E	illuminance meter
Instrument #3	E	diode-array spectroradiometer mounted with a cosine diffuser
Instrument #4	E	photopically corrected silicone photodiode with an opal glass diffuser
Instrument #5	L, x, y	tristimulus colorimeter
Instrument #6	L, x, y	diode-array spectroradiometer
Instrument #7	L	luminance meter

In a previous evaluation, we employed a prototype laser display system [7], but flexibility and cost directed us to use a substitute. For the flux saturation measurements, a small xenon flashlamp, with a 1.6 μ s pulse width (full-width half-maximum, FWHM) at a 60 Hz repetition rate. Although providing a wider pulse than a single pixel of the

flying-spot display, it is narrower than the accumulated pulses from measuring the multiple pixels of the laser display. The lamp is projected (with a condenser) onto a white sample in the comparator box, while a cathode-ray tube (CRT) monitor is placed before the other port. A mirror is used in place of a white sample to image the CRT in the bipartite image. We adjust the image through a software-controlled signal via a laptop VGA port.

For color saturation diagnostics, a simple source was built using three saturated sources. Three fiber optic illuminators illuminate an uncoated, closed-cell polystyrene cylinder through three narrowband interference filters. These filters, nominally at 450 nm, 550 nm, and 632.5 nm (with 8 nm, 9 nm, and 11 nm FWHM bandwidth, respectively) sit at the ends of black anodized aluminum into which a fiber-optic waveguide has been mounted. The cylinder has been coated with black material to eliminate leakage through the polystyrene. Figure 8 shows this source configured with the diagnostic comparator box and a reference source (a fiber optic illuminator illuminating a small integrating sphere) to perform trichromatic matching. To justify the use of the interference filters, we matched the 632.5 nm filter (illuminated with a fiber-optic waveguide) to a 632 nm He-Ne laser using the configuration in Fig. 8. The laser was despeckled with a rotating disk coated with a slightly diffusing material. The luminances of the two bipartite halves were measured using instrument # and agreed to within 3% of each other.

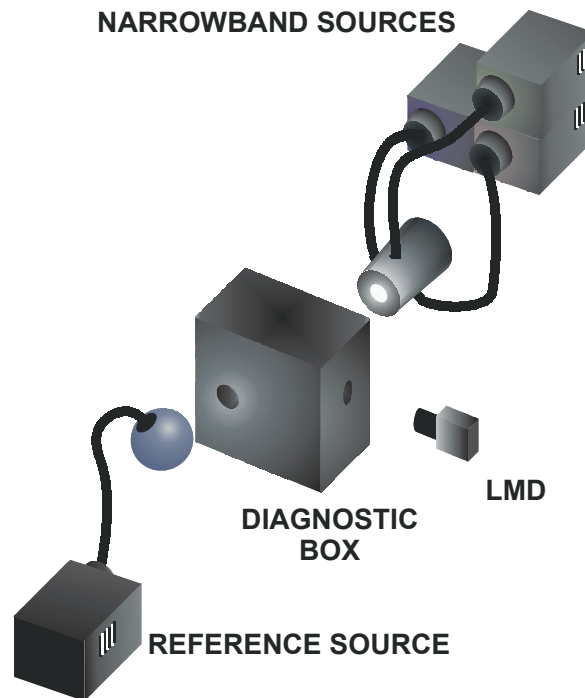


Figure 8. Color saturation evaluation with a three-filer source.

3.2 Flux Saturation

Initially, we matched the xenon lamp with the CRT using the diagnostic box, adjusting the CRT until a minimally distinct border was achieved between both halves of the bipartite image. Then each half was measured with both the luminance meter (instrument #7) and an illuminance meter (instrument #1). The results were reported in [8] so they are only described briefly here.

We measured the luminance directly. Because one half of the bipartite image was a mirror, we used an indirect method for determining the illuminance (the luminance may be matched, but because the CRT is not a projection system, the illuminances were not comparable). The reflectance of the white sample was calculated using a tungsten source in place of the xenon lamp by measuring the sample luminance through the viewing port and measuring the illuminance striking the sample. We could then ascertain the amount of light from the xenon lamp illuminating the sample by using Eq. 1, where E is the calculated average illuminance in lux, L is the measured average luminance of the sample illuminated by the lamp, and β is the luminance factor of the white sample (with the source at 45° and the

detector at 45°) as determined by the above procedure (in this case, $\beta = 1.02 \pm 0.01$, for the 45 / 45 configuration). The measured luminances of each half of the bipartite image (after matching) only deviated by an average of 1.3%. This established that instrument #7 was not affected by the width or energy of the xenon pulses. Thus, we could use the measured luminance for calculating the illuminance. The illuminance of the sample using the xenon lamp measures significantly less than the calculated illuminance based on the measured. The measured illuminance was almost 50% of its calculated value, indicating that the illuminance meter was probably saturating. Further investigation using NF filters confirmed this [7].

For this paper, we evaluated six instruments (#1 - #5 and #7) for saturation using alternative procedures, the results of which are discussed here. Using the method described in Fig. 4 (adjusting the distance between the LMD and the source), we measured the illuminance of the xenon flash lamp for these instruments. To determine whether the LMD detector or the amplifying electronics caused the saturation, several different ranging modes were used: auto-ranging, a manually fixed low range and a manually fixed high range. The in-house photodiode (instrument #4) was connected to both a 3.5 digit DMM and a 4.5 digit DMM for the same purpose. We calculated the illuminance using the luminance meter (instrument #7) for comparison. We did not verify the calibration of any of these instruments, but none was needed, for we were only concerned with the relative behavior of the LMDs.

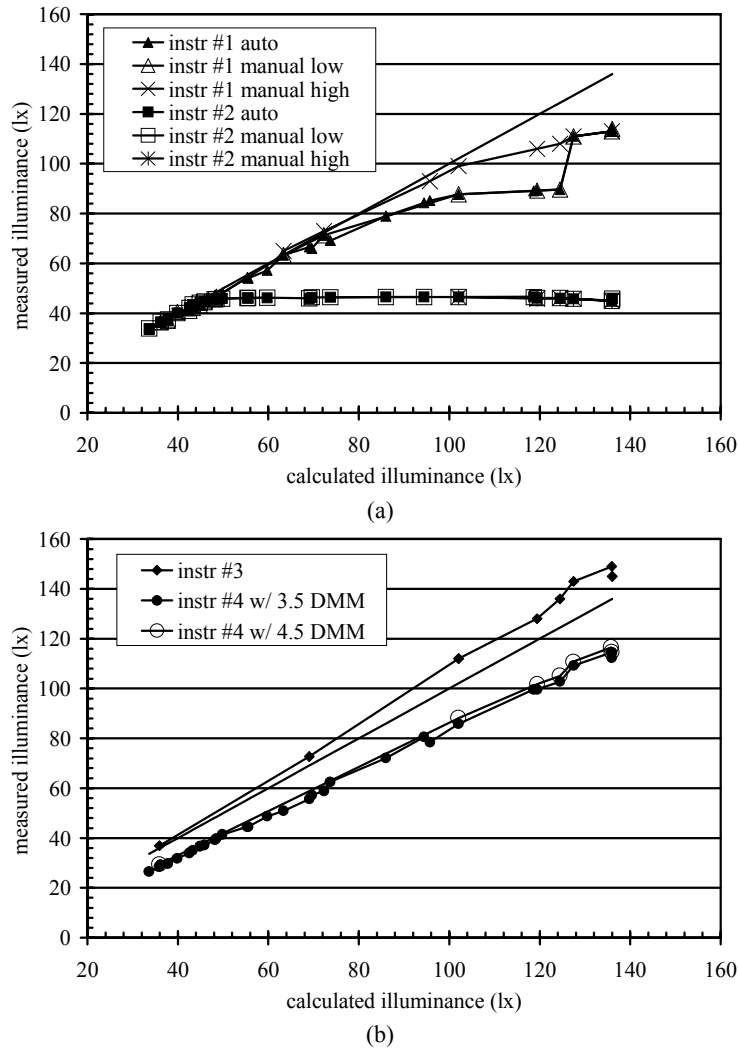


Figure 9. Evaluation of various LMDs for saturation using the varying-source method.

The photodiode array (instrument #4), regardless of the DMM used, and the diode array spectroradiometer (instrument #3) both demonstrated a linear correlation to the calculated data (see Figs 9a and 9b). The illuminance meters exhibited saturation, although at different levels. For instrument #1, the effect occurred at a higher flux level

for a higher range (lower gain), suggesting a possible electronic amplification clipping. Note the solid reference line placed in Fig. 9.

The above method could only produce a maximum illumination of around 150 lx. To determine the LMD behavior at even larger illuminances, we utilized the integrating sphere method (see Fig. 5), providing measured illuminances up to nearly 300 lx. Similar saturation was noticed for instruments #1 and #2, but none for the others (Figs 10a and 10b). Note that the luminance meter and the colorimeter were focused at the exit port, and placed 96 cm away from the front of the LMD lens to the exit port. Instrument #2, when forced into the highest range (lowest gain), no longer saturated, further indicating an electronic amplification problem (Fig. 11)

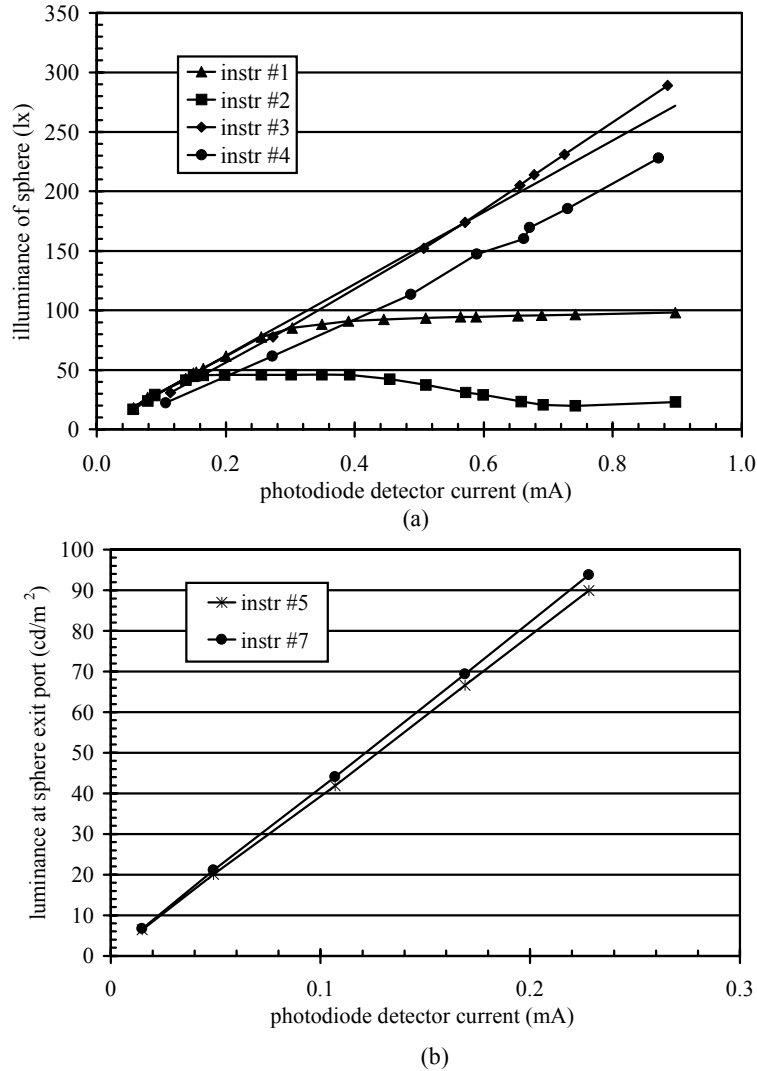


Figure 10. Evaluation of various LMDs for saturation using the sphere method.

3.3 Color Saturation

To investigate color saturation effects, we used the apparatus as configured in Fig. 8. Once again, matching both halves of the bipartite image so that a minimally distinct border is detected, we measured the resulting luminance, chromaticity and/or spectral distribution of each image half with instruments #5, #6 and #7. The spectral distributions of both sources are overlaid in Fig. 12.

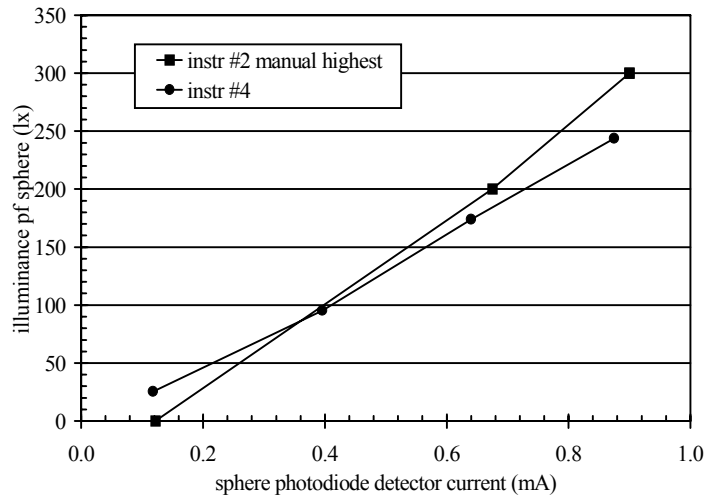


Figure 11. Evaluation of illuminance meter at its highest range (lowest gain).

Figure 13 presents the measured luminance difference between each image half for a series of different color temperatures. Because of the nature of the source, the range of color temperatures was not very large. Instrument #7, the luminance meter with the single photopic filter, fared well, with a maximum deviation of 1.3%. Instrument #5, the colorimeter with three color filters indicated a deviation of 3.5% for the worst case, suggesting a possible spectral mismatch of the filters. Instrument #6 had been designed to eliminate truncation errors during background subtraction, and thus the spectroradiometer results looked good as well. The standard deviation of these differences were under 2% for all instruments.

We also blocked off two filters at a time, measuring the luminance and chromaticity of each individual saturated color. Tables 2 and 3 show the results of these measurements, using Eqs. 2 and 3 to verify additivity. Note that the sum of the three individual source luminances and the luminance of the three combined sources are within 0.3% of each other. Instrument #6, the only LMD to provide spectral data, displayed similar additivity of the tristimulus results. Chromaticity values of all sources measured by the colorimeter and spectroradiometer are plotted in Fig. 14.

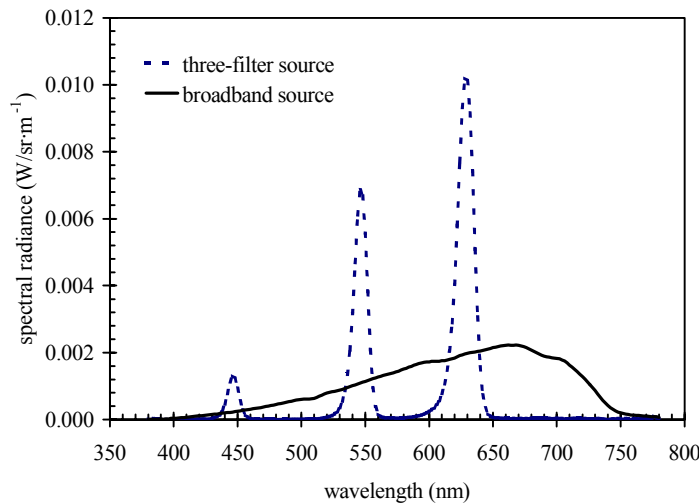


Figure 12. Spectrum of both sources overlain.

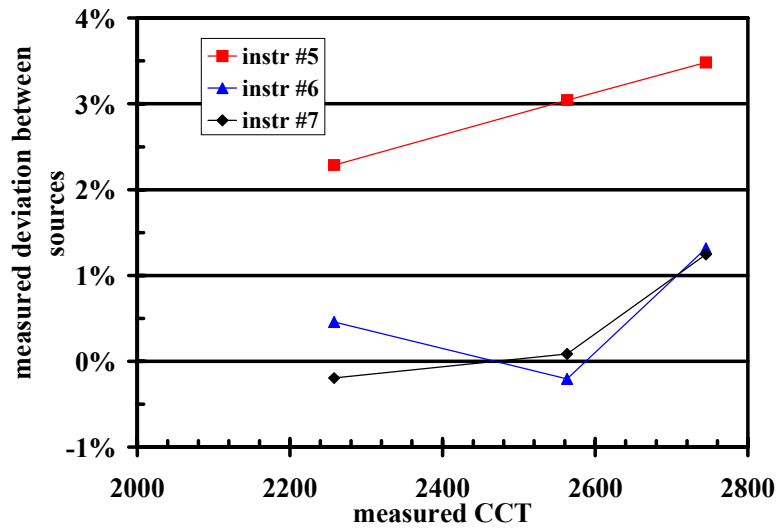


Figure 13. Luminance differences for various LMDs.

Table 2. Verification of the Additivity of Luminances for Various LMDs

LMD	Red source luminance (cd/m ²)	Green source luminance (cd/m ²)	Blue source luminance (cd/m ²)	Sum of luminances (cd/m ²)	Combined sources (cd/m ²)	Difference
#5	46.1	76.3	0.44	122.8	123	0.13%
#6	48.94	81.54	0.7040	131.18	131.2	0.01%
#7	46.86	77.72	0.457	154.04	125.4	0.29%

Table 3. Verification of the Additivity of Tristimulus Values For Various LMDs

source	X	Y	Z
red source	111.71	48.94	0.18
green source	31.00	81.54	1.48
blue source	4.89	0.70	23.85
sum of red, green and blue	147.60	131.18	25.50
combined source	148.14	131.20	25.97
difference	0.37%	.01%	1.81%

3.4 Uncertainty Analysis

The luminance meter passes the integration test, with an average measured luminance deviation of 1.3% between the two displays when the perceived brightness between the two displays matched (see Table 1). The measurement relative expanded uncertainties[‡] are approximately 3% for the luminance measurements and 5% for the illuminance measurements. These results are based on an average of tests taken over the course of the research. For the matching of color and luminance, it was determined that the standard deviation resulting from lack of sensitivity of changes in luminance was approximately 0.53%, and the reproducibility of the matching was approximately 0.76% for the luminance, and ± 0.004 for the x- and y-coordinates.

[‡] Throughout this paper, all uncertainty values are given as an expanded uncertainty with coverage factor $k = 2$.

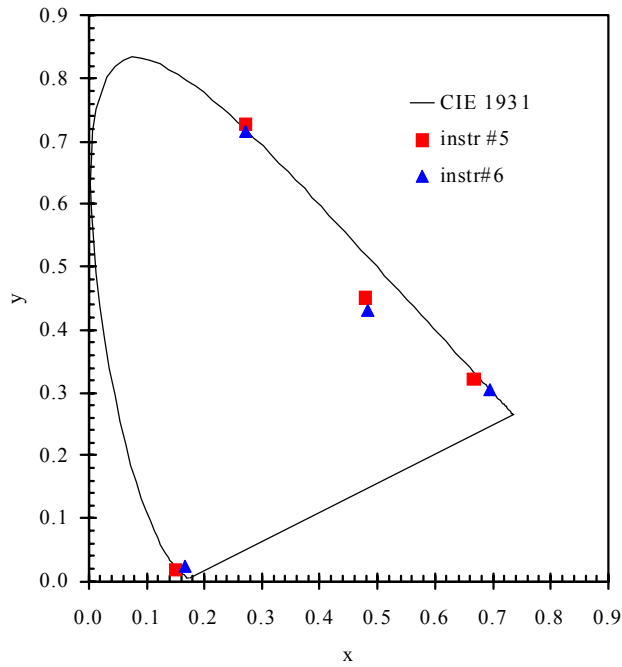


Figure 14. Chromaticity values using different LMDs.

4. CONCLUSION

A few of the instruments exhibited limitations because of the large instantaneous flux required at each pixel to adequately illuminate projection screens in certain conditions. Subsequent examination of the current output of these meters verified that the pulse overloaded the signal amplification. However, the lack of evidence of a significant color saturation effect should not suggest that a three-narrowband source influence does not exist. A different choice of interference filters may demonstrate larger errors. Indeed, highly saturated colors can cause LMDs to report inaccurate color information resulting from spectral mismatch or other errors [4,9]. The data does suggest that a constant brightness-to-luminance ratio exists for white sources of different spectral distributions that have been brightness matched, although we did not examine higher luminances. Neither did we explore the effect of speckle on the brightness-to-luminance ratio, since this property is deemed undesirable.

Some of the limitations described above can be compensated for, often quite easily. If setting the meter at a higher range (lower sensitivity) does not provide an adequate solution, a set of calibrated metal-evaporated ND filters may prevent the LMD from saturating [8]. Colorimeters may be calibrated for a specific source, and transformations may be possible to correct for variations in spectral distribution using a four-color transformation matrix [10, 11]. Truncation of data in spectroradiometers may be bypassed if the raw diode-array data is available [4]. The diagnostics can then be employed to verify performance.

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