Diagnostics for light measuring devices in flying-spot display measurements

Paul A. Boynton[*a], Edward F. Kelley[a], Susan Highnote[b], Randy Hurtado[c†]

[a]National Institute of Standards and Technology[‡], 100 Bureau Drive, Gaithersburg, MD 20899

[b]Highnote Enterprises, La Jolla, CA 92037

[c] Laser Power Research, 12777 High Bluff Drive, San Diego, CA 92130

ABSTRACT

Flying-spot displays, such as some laser projection displays (for example, see [1, 2]), use a high-energy beam as a light source that scans the image across the display screen. Each pixel can be a narrow, high-energy pulse. 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 light output due to the unique characteristics of the source. The LMD may be unable to properly integrate the narrow pulses, or the high-energy signal may saturate the detector. As in all areas of metrology, it is essential to verify that the instruments used are providing the desired information . A diagnostic has been developed that allows for an evaluation of LMDs for use in measuring flying-spot displays. This method tests for both integration and saturation errors using a bipartite comparator and a neutral density filter. Errors to due the saturation of the LMD by the flying-spot display is demonstrated. The construction and procedure of the diagnostic is described. Limitations of the technique as well as sources of error are presented.

1. INTRODUCTION

Some experts report experiences with measuring a high-energy beam scanning across the display screen that proved difficult due to limitations of the LMDs [3]. Specifically, how does the characteristics of the display affect how one measures its brightness? If the number of photons striking the detector window is high enough, the detector will saturate, although this limit depends on the integration time as well.

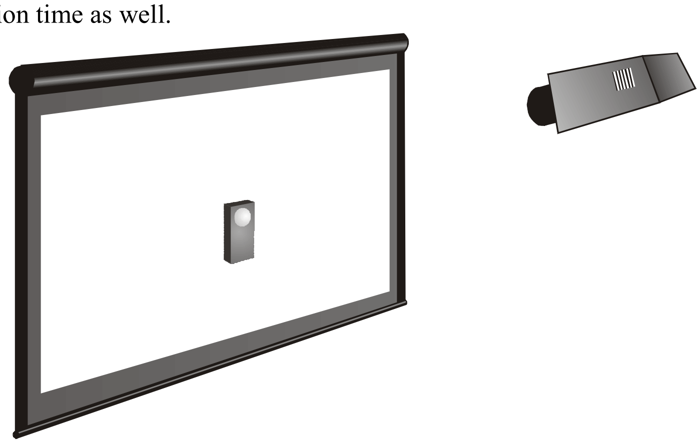

Figure 1. Measuring display light output.

[*] Correspondence: Email: boynton@eeel.nist.gov; Telephone: 301-975-3014; Fax: 301-926-3534

[†] Worked for Laser Power Research during the time of the flying-spot measurements.

[‡] Electricity Division, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce.

Suppose we have a green CW laser that produces a P=5 W beam and displays an N=1024 $\times$ 768 pixel image. As the flying-spot scans by, a point on the screen would see a "pixel" at $p = P/N = 6.36\ \mu W$ (see figure 1). The conversion to luminous flux is approximately $\Phi_p = k \times p = 4.34$ mlm, where $k = 683$ lm/W. Assume that the area of the pixel projected onto the screen to be $A_p = 15\ \mu m^2$. Since $\Phi_p = E \times A_p$, the illuminance E is easily calculated to be $\Phi_p / A_p = 284$ lx.

To determine the luminance, keep in mind that the illuminance is related to the luminance by $L = (\rho/\pi) \times E$, where ρ is the luminance factor of the screen. To simplify these calculations, assuming we have a perfectly diffuse Lambertian reflector (ρ=1). Thus $\Phi_p = \pi L_p \times A_p$ and $L_p = \Phi_p/(\pi A_p) = 90.4\ cd/m^2$. The light output over the entire image would be $\Phi_{total} = A_p \times N \times E$ or about 3400 lumens. However, the instantaneous luminance at each pixel would be $L_I = \Phi_{total}/(\pi A_p \times N) = 3.85 \times 10^7\ cd/m^2$. At a refresh rate of 60 Hz (Δt = 16.67 ms), the average energy per pixel would be $K = p \times \Delta t = 106$ nJ. Could this large signal possibly saturate the LMD?

Another possible source of error is related to the width of the laser pulse. For the above example, the pixel pulse width $\delta t = \Delta t/N = 21$ ns. If the LMD has an integration time on the order of a few milliseconds, will it inaccurately measure the light output? Obviously a diagnostic would prove useful in answering these questions.

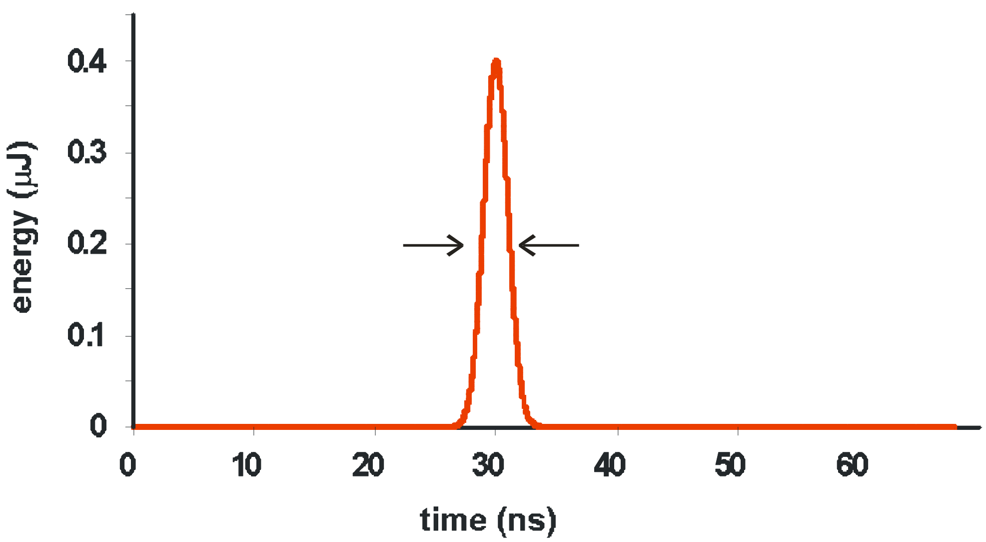

Figure 2. Flying spot "pixel"

2. BIPARTITE COMPARATOR DIAGNOSTIC

2.1 Bipartite Comparator A two-part diagnostic has been developed to evaluate the performance of LMDs. We projected a flying-spot display image onto one-half of a bipartite Lambertian reflectance white sample, and a conventional display image onto the other half (see Figs. 3 and 4). One display was adjusted (visually) to the same perceived brightness and color as the other. Then both samples were measured with a luminance meter and an illuminance meter. If both samples appeared the same brightness but measured differently, this would indicate that the LMD could not correctly measure the flying-spot display. Placing a neutral density filter (NDF) of known transmission in front of the display should reduce the measured luminance or illuminance by a predicted amount. If not, then the LMD is being saturated by the high-energy pulse of the flying spot. If it does reduce by the predicted amount, then the LMD error is due to its inability to properly integrate the narrow pulses.

The five-sided box, manufactured with black plastic material, rests upon a 25 cm x 15 cm black-anodized breadboard with tapped holes. Three 50 mm holes have been 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 (see Fig. 2).

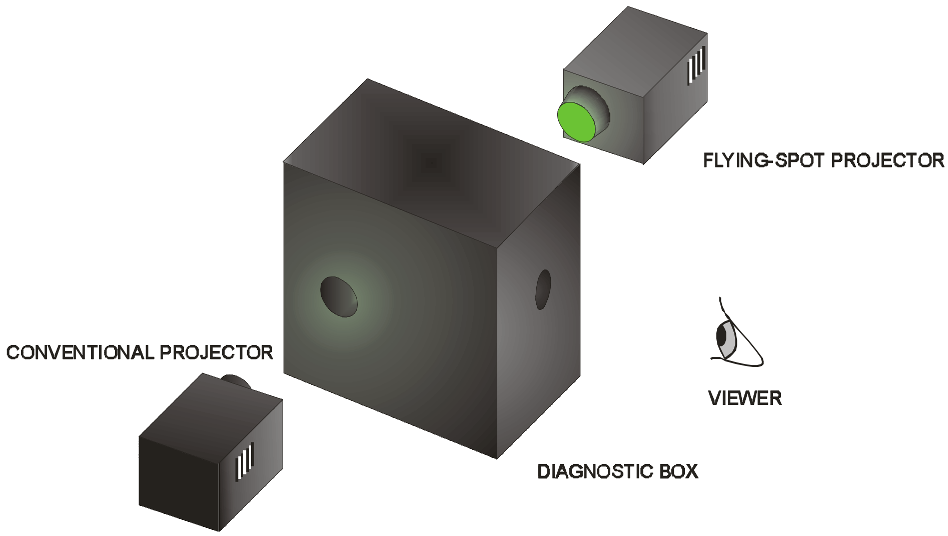

Figure 3. Comparator box

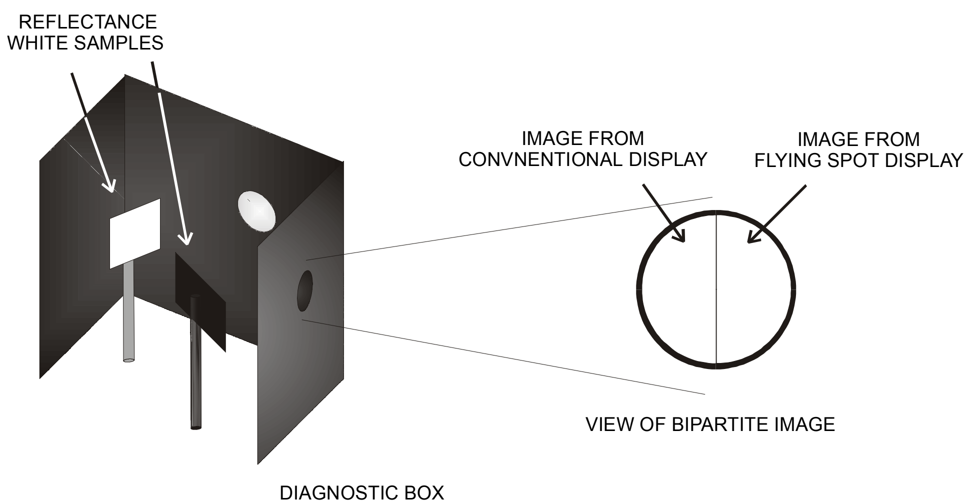

Figure 4. Bipartite image.

The flying-spot display is projected into the comparator box and onto the facing white sample The test pattern produced by the reference display should be a uniform flat field, and able to match the color of the test projector image. The conventional display should be projected through the opposite port onto the other white sample, displaying the same flat field pattern. A signal generator or a computer can drive this latter display, and its color and brightness adjusted to match the flying spot image. This matching may differ due to viewer preferences. If a reference projector is not available, then a mirror can replace a white sample and a conventional emissive display can be used for reference.

Once the brightness and color match has been achieved, use the LMD in question to measure each half of the bipartite image. A luminance meter can be aimed through the viewing port to measure the white samples directly. An illuminance meter can be lowered down through a slot in the top of the comparator box and placed in place of the white sample, and measure the luminous flux per unit area. The deviation between the measurements of both halves indicates the degree of confidence you have in the performance of the LMD in measuring the light output of the particular flying-spot display. For illuminance meters, the distances to the projectors can be critical particularly if the projectors are close (within a meter or so) to the diagnostic box.

If the two displays differ significantly, then proceed to the next step. We make no attempt to determine how much deviation is acceptable, as this can be a function of the uncertainty of the instrument and of the particular application. If you are concerned with 10%, and the display measurements differ by 5%, you might determine that any measured difference is negligible for you application. That must be your careful decision. However, even if your results match to within 1%, we still recommend performing the NDF test.

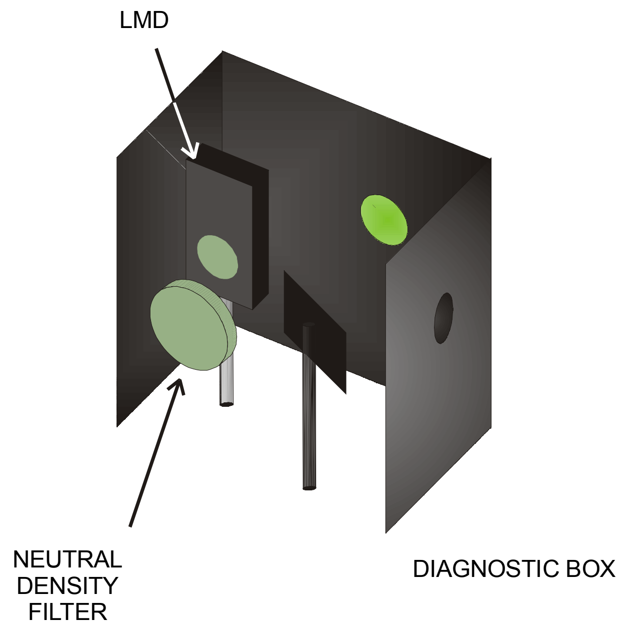

Figure 5. Saturation test using a neutral density filter.

Take a stable light source and measure the luminance. Then place a NDF between the source and the LMD, and measure again. The ratio of the measurements without and with the NDF will provide a short-term, relative calibration of the filter's transmission. Perform this test with the light source set at various light-output levels to verify that the instrument's response is linear. Next, measure the flying spot display, both with and without the NDF in place (see Fig. 3). The transmission should be the same. A significant deviation would indicate that the display is saturating the LMD.

2.2 Description of other equipment[§]**.** For this experiment, we used two projection displays. The flying-spot display was a developmental model that "wrote" directly onto the screen. This system, mounted onto an optical bench, uses a microlaser [4] modulated by a linear spatial light modulator, and scanned by a rotating polygon mirror in a horizontal direction and by a galvanometric scanner in the vertical direction. The 532 nm, 2.5 W beam produced a spot that travels across the entire screen at 60 Hz. The projector was operated at NTSC resolution.

[§] Any reference to a particular manufacturer is identified in this paper to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does in imply that the equipment identified is necessarily the best available for the purpose.

Since the flying-spot display had only the green laser in operation, we chose to use a LCD-modulated display with a laser source as the control [1]. This projector uses a 1280 by 1024 reflective-LCD panel to modulate two microlasers (at wavelengths of 532 and 457) and a red diode laser (with a wavelength of 652 nm). The laser operated in continuous mode with the beam spread to fill the entire LCD panel. The unit operated at a refresh rate of 60 Hz. We used the unit with the green laser switched on to match the chromaticity of the flying-spot display.

We chose to measure the displays with two simple, hand-held LMDs: a luminance meter and an illuminance meter. The luminance meter used a photodiode and lens system with a 2 º measurement aperture. The illuminance meter used a cosine receptor head, and both operated off of alkaline batteries.

3. RESULTS

The luminance meter passed the integration test, with an average measured luminance deviation of 1.3% between the two displays when the perceived brightness between the two had been matched (see Table 1). The uncertainty[**] of these measurements was approximately 10%. These results are based on an average of tests, with members of the research group serving as subjects. To be thorough, we also used the NDF test (Table 2) using a NDF with an optical density of approximately 0.2. After verifying the filter density with a non-scanning light source, we determined that the NDF transmission measurements averaged 69.7% for both displays, indicating that a saturation condition was not present.

Table 1. Test for LMD's Ability to Measure Flying-Spot Displays

	luminance meter			**illuminance meter**		
	flying spot ***cd/m²***	**LCD** ***cd/m²***	**deviation**	**flying spot** ***lux***	**LCD** ***lux***	**deviation**
average	106.7	105.3	1.3%	640	651	9.1%
std. dev.	5.4	2.1	4.9%	127	26	6.7%
range	17.9	8.2		402	87	
max. dev.			7.6%			22.9%

Table 2. Test for Possible Saturation Limitations of LMDs

	luminance meter		**illuminance meter**	
	flying spot ***cd/m²***	**LCD** ***cd/m²***	**flying spot** ***lux***	**LCD** ***lux***
no NDF—average	159.0	154.9	87	113
with NDF—average	110.9	108.8	56	79
measured transmission of NDF	69.7%	69.7%	65%	70%

The same could be said for the illuminance meter, but some alignment challenges created difficulties in reducing the associated measurement error. Measuring illuminance of a light source is dependent on the distance of the detector to the source, proportional to the inverse of the distance squared. Therefore at close ranges, small displacements of the illuminance meter can introduce large errors. This angular sensitivity proved a significant factor in this experiment. The laser display, as described above, was an early prototype still mounted onto an optical table. Due to the room configuration, the comparator box could be placed no more than 2 m away. Thus the measurements became very sensitive to slight changes in angular position.

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

Related to this configuration limitation was the resulting fact that we measured a field width and height of approximately 66 pixels. Thus the total amount of light being measured was at the lower limits of the LMDs. This proved to be a significant limitation, as shall be shown later in this paper.

4. ANALYSIS

4.1 Alignment errors. This can be seen by the data in Table 3, which shows the results of a reproducibility determination. Using both projectors, we displayed the same flat-field image. Using different operators, we moved the LMD into position, measured, and moved out of position. This gave us an indication of the reproducibility of the measurement (as opposed to the repeatability). The larger standard deviation for measuring the flying-spot display would indicate the difficulty in maintaining a reproducible positioning of the illuminance meter. We observed similar variation by slightly turning the meter a few degrees off normal in several directions.

Table 3. Reproducibility of Measurements

	luminance meter		**illuminance meter**	
	flying spot *cd/m^2*	**LCD** *cd/m^2*	**flying spot** *lux*	**LCD** *lux*
reproducibility (std. dev.)	2.50	2.42	28.12	10.12

4.2 Cross-corruption. One possible source of error could result from cross corruption from the two displays. The light entering one port could reflect off the sample and other surfaces, contaminating the measurement of the other sample. Thus we devised a simple test to determine if such an effect was present. Placing two different wide-band color filters (one blue, the other red) over each of the ports, we then projected light through each port using common white-light projectors. Then we measured the spectral distribution of the light reflecting off of each white sample with a spectroradiometer (see Fig.6) in three conditions: one source on, the other source on, and finally, both sources on. Each spectral distribution showed negligible effects (less than 1%) due to the presence of the other source.

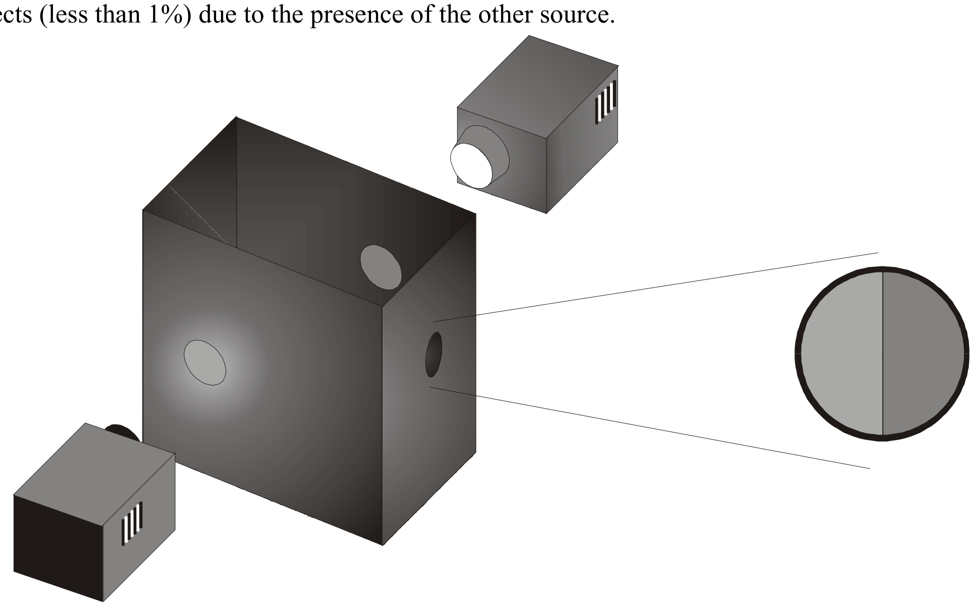

Figure 6. Cross-corruption evaluation

4.3 Alternative verification. Since the availability of a suitable flying-spot display that was not limited in measurement distance was not possible at the time, an alternative source was considered. We attempted to simulate such a display by devising a “Pockels-cell pulse plucker” [5]. Figure 5 shows a block diagram of the set-up. A pulse source flashes a xenon lamp, creating a 1.6 μs pulse. The pulse source, slightly delayed, also engages a controller that switches the electro-optic Pockels cell, allowing the light pulse to pass through. The cell would, however, be switching on for a duration of 40-50 ns, essentially plucking the narrower pulse from the wider one produced by the flash lamp. The most challenging aspect of this configuring was never realized, due to the difficulty and expense in developing a repeatable fast-switching high-voltage controller to operate the cell.

Thus we could perform supplemental measurements with only the xenon lamp in place. The lamp was projected (with a condenser) onto a white sample in the comparator box, while a cathode-ray tube (CRT) monitor was placed before the other port. A mirror was used in place of a white sample to image the CRT in the bipartite image. We adjusted the image through a software-controlled signal via a laptop VGA port.

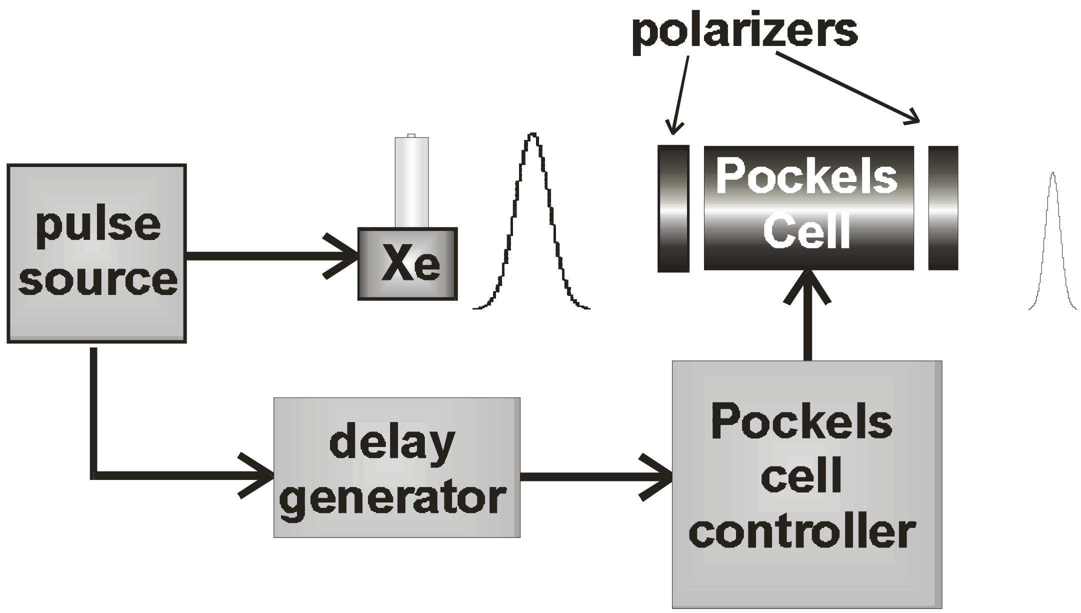

Figure 7. Pockels cell pulse plucker.

After matching the two displays, we measured the luminance directly. Since one half of the bipartite image was a mirror, we used an indirect method for determining the illuminance (the luminance may be matched, but since the CRT is not a projection system, the luminances, of course, would be significantly different). 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 the following equation:

$$E = L \times \pi / \rho \;, \tag{1}$$

where E is the calculated illuminance in lux, L is the measured luminance of the sample illuminated by the lamp, and ρ is the luminance factor of the white sample (with the source at 45º and the detector at 45º) as determined by the above procedure.

In the case of the luminance meter, we obtain similar results to the earlier tests, as shown in Table 4. The measured luminances of each half of the bipartite image (after matching) only deviated by an average of 1.3%. This established that the luminance meter was not affected width or energy of the xenon pulses. Thus we can use the measured luminance for calculating the illuminance.

In contrast to the earlier tests, the illumination of the sample by the xenon lamp measured significantly less that the calculated illuminance based on the measured luminance (see Table 4.). The uncertainty of these measurements was improved due to better control over positioning of the sources and brightness of the images. The expanded uncertainty was approximately 2%. The reproducibility of the measurements improved to a standard deviation of 0.55 cd/m^2 for the luminance measurements and 0.72 lux for the illuminance measurements.

Table 4. Comparator Diagnostic Using a Flash Lamp

	luminance meter			**illuminance**		
	flash lamp ***cd/m²***	**CRT** ***cd/m²***	**deviation**	**measured flash lamp** ***lx***	**calculated based on luminance measurement** ***lx***	**deviation**
average	53.41	52.72	1.3%	88.3	167.8	47.4%
std. dev.	.300	.051	0.5%	.68		
range	0.53	0.10		1.5		
max. dev.			1.9%			48.0%

To determine whether this deviation from the predicted illuminance resulted from the saturation of the LMD by the xenon pulses, we performed an NDF test with a filter with a nominal optical density of 0.2, the results of which can be found in Table 6. The NDF was certified to be 0.2 using tungsten source, but the illuminance meter incorrectly indicated the NDF density. This indicated the illuminance meter is being saturated. We further examined the saturation effect by lowering the illuminance until no saturation is seen. We accomplished this by using an NDF with a nominal optical density of 1.0. The xenon-lamp-illuminated white sample was measured by both the luminance meter and the illuminance meter, with the NDF in place, and with the filter removed (see Table 7). Based on the illuminance data, we then calculated the luminance, using equation 1. An agreement between the calculated luminance and the measured luminance would indicate no saturation effects. (The correct measured transmission establishes the linearity of the luminance meter.) Note that with a 1.0 NDF in place, the correct illuminance is measured, further suggesting a saturation effect of the illuminance meter when no NDF is used.

The difference between this test with the xenon lamp and the earlier test with the laser projector due to the boundaries necessitated by the room configuration. As mentioned earlier in the paper, the measurement field of the illuminance meter was measuring a cluster of about 66 pixels, due to the limited distance of the projector. Since we had more pixels available to create a reasonable brightness, each pixel had less instantaneous power than if we were measuring the image projected onto a larger area. Furthermore, alignment difficulties created a larger measurement uncertainty that may have masked any saturation effects.

Table 6. Test for Possible Saturation Limitations of LMDs

	illuminance meter	
	flash lamp ***lx***	**tungsten source** ***lx***
no NDF—average	84.2	30.2
with NDF—average	73.1	19.9
measured transmission of NDF	87%	66%
measured optical density	0.06	0.18

Table 7. Test to Verify Saturation Effects Using Xenon Flash Lamp

	luminance meter cd/m²	**illuminance meter lx**	**calculated luminance cd/m²**
no NDF	**71.0**	88.2	**29.5**
with NDF	**7.45**	22.3	**7.45**
measured transmission of NDF	10%	25%	
measured optical density	0.98	0.60	

7. CONCLUSION

When measuring flying-spot displays with conventional LMDs, we must be aware of possible limitations. The measuring instrument may or may not be influenced by the optical characteristics of the high-powered flying-spot scanning across the measurement aperture. The contrasting responses shown by the LMDs used in this research may be do to differing design implementations; any further speculation goes beyond the scope of this paper. Of greater importance to manufacturers and users of flying-spot systems is to remember that, as in all areas of metrology, it is essential to verify that your measurement instrumentation is providing the correct information that you desire. This relatively simple technique can verify or eliminate the performance concerns of a particular LMD and display combination in terms of integration and saturation.

REFERNECES

1. R. Bergstedt, et. al., "Microlaser-based displays," *Proceedings of the SPIE: Cockpit Displays V: Flat Panel Displays for Defense Applications* **3057**, pp. 362-367, 1997.

2 R. Martinsen, et. al., "Diode-pumped vanadate lasers for variable resolution video projectors," ," *Proceedings of the SPIE: Fabrication, Testing, and Reliability of Semiconductor Lasers III* **3285**, pp. 133-141, 1998.

3. W. Bohannon, "Scanning Laser Projectors," *Information Display* **13**, pp. 32-36, 1997.

4. D. Hargis, et. al. "Diode-pumped microlasers for display applications," *Proceedings of the SPIE: Fabrication, Testing, and Reliability of Semiconductor Lasers III* **3285**, pp. 115-124, 1998.

5. P. Boynton, "Evaluation of Light Measuring Devices for Flying-Spot Display Measurements," *Council for Optical Radiometric Measurement (CORM) Annual Conference, Session IV: Optical Metrology of Displays,* Gaithersburg, MD 1999.