Meeting the Metrology Needs of the Microdisplay Industry

Paul A. Boynton, Edward F. Kelley and John Libert

National Institute of Standards and Technology

100 Bureau Drive, Gaithersburg, MD 20899

Abstract

Measuring the optical characteristics of a microdisplay produces challenges to traditional display metrology. When using light-measuring devices to measure scenes having high contrasts or wide color variations, the instruments suffer the effects of veiling glare or lens flare, thereby inaccurately measuring the luminance or color, especially for darker luminances.

A simulated-eye-design (SED) camera is being developed to attempt to reduce unwanted light contamination by copying some of the characteristics of the human eye. A discussion of the first prototype will be presented. Adequately characterizing the reflection properties of a raw microdisplay can also prove difficult due to the presence of the haze component in the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance distribution function (BTDF). In the general case, there are a minimum of three components with a minimum of four parameters that are required to specify reflection—specular (distinct image), Lambertian, the haze peak and the haze width. Thus, a minimum of four measurements are needed, and probably more, to characterize reflection. Several simple techniques to better characterize reflections—techniques that are readily accessible using simple equipment, will be reviewed.

Finally, the Video Electronic Standards Association (VESA) plans to incorporate microdisplay metrology into a future version of the Flat Panel Display Measurement (FPDM) standard will be discussed.

1. Introduction

Microdisplay metrology involves two basic areas: measuring the finished display and measuring the raw display (minus the optics). Based on our discussions with representatives in the microdisplay industry, not only has the necessary metrology not been well established, but also the accuracy of the instrumentation used may be in question. At present, NIST is addressing these concerns on several fronts; these techniques and solutions are still under research.

Figure 1. Stray light within detector—veiling glare.

1 Correspondence: Email: boynton@eeel.nist.gov; Telephone: 301-975-3014

2 Electricity Division, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Technology Administration, U.S. Department of Commerce. This is a contribution of the National Institute of Standards and Technology and is not subject to copyright.
2. Measuring Near-Eye Displays

2.1 The problem.

Measuring miniature displays can prove to be quite a challenge. Many of the difficulties of larger display measurements (such as contrast) remain present and even become more difficult for the tiny displays. The culprit is the limitations of the light-measuring devices (LMD) with respect to their ability to perform measurements that compare well to the performance of the human visual system. Ideally, we want to have an LMD that we can place in the exact position of the human eye, can be rotated and positioned similar to the eye, has the eye’s proper aperture, and has the eye’s ability to reduce veiling glare.

It is this last characteristic that may be the most difficult to mimic. Measurement of luminance or color can be straightforward when the displays produce a full screen color or grey scale image. However, when detail is introduced, measurements of the details can be corrupted by veiling glare mixing the luminances or colors [1]. Glare results from many sources: light outside the field-of-view of the light-measuring device (LMD) scattering and reflecting at the lens surfaces; glass imperfections; dust and dirt on the lens surfaces; the barrel, iris, and other mechanical parts of the lens; and reflections between lens surfaces.

Figure 1 demonstrates how a conventionally photopically corrected thermoelectrically cooled scientific grade charge-coupled device (CCD) camera with a complicated lens and many air-solid surfaces can introduce reflections into the measurement. One ray from a white area on the object is shown reflecting off of various surfaces onto the image of the black rectangle. (Note: this diagram is not a ray tracing, but is for illustrative purposes only.)

Figure 2 illustrates how the veiling glare can corrupt the measurement of contrast. An 8 x 8 checkerboard pattern is displayed on an active-matrix liquid crystal display (AMLCD). A plastic strip is placed vertically to completely cover one column of blocks on the left. A black plastic rectangle the size of one block is placed over a single black block on the right. These black plastic masks are called replica masks, for they offer a measurement of the veiling glare contribution.

The image on the left (in Fig. 2) was taken with a scientific grade CCD camera image (such as that in Fig. 1) with the full dynamic range of the image (approximately 16 bits). The right-side image in Fig 2 is the same photograph with the dark regions intensified to illustrate the introduction of glare. In both images, the CCD counts are proportional to the luminance of the display. The black rectangle luminance $L_b$ measures approximately 310 counts, and the white rectangle luminance $L_w$ is 22200 counts, giving a contrast ratio of $L_w/L_b$ of 72:1. However, the veiling glare contribution must be accounted for. The contribution of veiling glare is observed in the replica mask luminance $L_g$ that measures approximately 230 counts. Thus the true black luminance $L_b = L_w - L_g$ is 80 counts, indicating a nearly 300% veiling glare contribution to the black luminance measurement. The true contrast ratio is then $L_w/L_b = 278:1$, which is closer to the more accurately measured value of 250:1 when by using aperture and frustum (cone with apex cut off) masks [2].

For large-area luminance and color measurement, a glossy black frustum can be used to minimize the effect of the glare [2].
However, if the cone aperture size is small (less than 5 mm), as it would be for microdisplay measurements, then the cone may interfere with the measurement. Reflection and scattering off the edge of the hole into the LMD or back onto the surface of the display can contribute to the stray light. Therefore, another method is needed to obtain these small-area measurements.

2.2 The simulated-eye-design camera.

NIST has developed a simulated-eye-design (SED) camera [3] in an attempt to minimize the effects of veiling glare. The SED technology is an optical system that attempts to improve high contrast measurements by removing various sources of reflections, much as the human eye. In the prototype, a simple glass lens is placed before a CCD, but instead of air, the area behind the lens is liquid filled, right up to the silicon chip of the CCD. The glass cover plate that normally protects the CCD has been removed. The barrel of this liquid-filled lens is made with black acetal plastic to further minimize reflections (see Fig. 4). The use of liquid-filled cameras is not new [4,5], but to our knowledge, it never been applied to improve contrast measurements.

Since the CCD camera is exposed to the liquid, a silicon-based liquid (polydimethylsiloxane, trimethylsiloxy-terminated) is used, having a viscosity of 1 cm²/s, and an index of refraction $n_2 = 1.41$. The lens on the camera is an uncoated 25 mm diameter plano-convex lens with a focal length of 25 mm, and an index of refraction of $n_1 = 1.673$. The reflectance $R$ for normal incidence is

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

For the glass-liquid interface, $R = 0.73\%$, whereas for a normal air-glass interface $R = 6.3\%$. An aperture of 5 mm is placed directly in front of the lens.

In order to evaluate the contrast enhancement of the SED, this design has been compared to a camera of similar design but air-filled rather than liquid-filled. A uniform light source with an exit port diameter of 15 cm is placed 55 cm away from each camera lens. At the exit port center is placed a 50 mm square matte-black plastic mask, large enough to fill the entire CCD image. Thus no light from the source is falling directly onto the CCD detector, and any light measured would result from veiling glare. The source, uniform to within 2% across the exit port, uses an adjustable fluorescent lamp with linearity better than 7%. A photodiode is used to monitor the source luminance.

The liquid-filled camera proved a 2.7 factor of improvement over its air-filled counterpart (for details, see Ref [3]). A small improvement, perhaps, but this is the first prototype. We plan to improve the optics in several ways. First, more refined filtration techniques can be utilized to improve the purity of the silicon-based fluid. Even minute particles in the fluid will cause scattering of light within the camera. A better index matching of...
the liquid to the solid may be possible which would further reduce reflections. Polishing and painting the sides of the lens and interior surfaces of the camera would increase stray-light absorption. Placement of the camera aperture and exploration of different lens geometries are also being considered. The goal is to produce a camera that has a glare factor significantly less than 0.1%. This would provide a measurement tool that could be placed at the pupil point of the eye and come close to measuring what the eye truly sees.

3. Raw Display Metrology

3.1 The problem.

Adequately characterizing the reflection properties of a raw microdisplay can also prove difficult due to the presence of the haze component in the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance distribution function (BTDF) [6]. The display industry has concerned itself with the two historical types of reflection: diffuse and specular. Unfortunately, reflection characteristics can be much more complex than these two parameters. To illustrate this, observe the data in Fig 4. Here, a BRDF was measured for a sample material using the configuration on the left. As the plot shows, there exists a specular peak, a nearly flat Lambertian (inadequately referred to as diffuse) component, and then a transitional component that occurs between the two. This latter component, called haze, is manifested as a fuzzy ball on a display surface.

Over the years, usually only two measurements have been made to characterize the reflection (diffuse and specular). Sometimes three measurements are made. In the general case, a minimum of four parameters that are required to specify reflection—specular (distinct image), Lambertian, and haze with a peak and width. Two measurements (equations), four unknowns—that means that if we only make two measurements, then there are an infinite number of displays that will measure identically and look entirely differently to the human eye! Thus, a minimum of four measurements are needed, and possibly more, to accurately characterize reflection.

The haze parameters are particularly difficult to measure, for the measurement can be sensitive to the geometry of the apparatus. Thus, such parameters as the LMD distance, lens diameter, focus, source size, and source distance, come into play. For example, in one measurement configuration, a 4° misalignment of the source can result in a 30% error in the measured reflected luminance. Furthermore, haze reflection need not be symmetrical. Star patterns and spikes further complicate a full characterization of reflection, requiring a complete, time and data intensive BRDF measurement. Separating out the specular component also may be daunting. A finer sampling of data with a smaller measurement aperture (typically much less than 1°) is required to accurately capture the specular peak and separate it from the haze peak. Note that the graph in Fig. 4, the BRDF extends almost four orders of magnitude. Some displays only have haze and can exhibit five orders of magnitude or more in reflected luminance, with no appreciable Lambertian component.
3.2 Measurement solutions.

Ideally, reflection measurements must provide results that are not subject to small apparatus imperfections or irregularities or choice of equipment. They also need to be reproducible and unambiguous. Several simple techniques to better characterize reflections are being investigated at NIST—techniques that are readily accessible using simple equipment: (1) ambient reflection using the equivalent of an integrating sphere, (2) reflection of a small annulus (that allows the separation of the specular and haze peak), (3) reflection of a variable aperture source (that also allows the separation of the haze peak and specular components), (4) simplified BRDF measurements avoiding the details of the peak, and (5) making CCD measurements to fully characterize the reflection properties (for those who have such equipment).

3.1.1 Directed Hemispherical Reflectance.

Assume a worst-case scenario: uniform light from all directions illuminating a display, such as bright fog in a bubble helicopter. To make this measurement, place the display into a large integrating sphere (see Fig. 5) and tilt the display so that the measurement hole is approximately 8° off from the display normal. The resultant measurement gives you the directed hemispherical reflectance, \( \beta_{hk} \). A variety of apparatus can be used to reproduce sufficiently the uniform hemispherical surround conditions, such as rectangular sources with large exit ports. The results tend to be insensitive to apparatus configuration and angular alignment.

3.1.2 Annulus method.

A technique to separate out the haze and specular peak is illustrated in Fig. 6. One can separate out the haze peak \( h \) from the specular reflectance \( \rho_s \) by essentially eclipsing the specular component with a tiny black annulus placed in the center of a small source. By comparing the measurements with and without the annulus in place, one can estimate the specular and haze peaks. Unfortunately, corrections for veiling glare must be made in the luminance meter (see Ref [2]).
3.1.3. Variable aperture source method.

Another approach to isolating the specular peak, shown in Fig. 7, involves measuring the reflected luminance of the source for a series of decreasing source apertures. As the aperture radius approaches zero, the Lambertian and haze components become smaller. If a quartic curve is fitted to the data for small radii, the extrapolation to zero will reveal the specular component (see graph in Fig. 7). Be aware that the extraction of any haze information may be non-unique or uncertain.

3.1.4 Simple BRDF measurements.

To approximate the Lambertian component, measuring the BRDF for large angles (θ ≥ 70°) may suffice (see Fig. 8). Using a source with an angular diameter of 1° or less, the luminance can be measured as a function of angle from the normal for angles greater than 5° or 10°. This avoids the high-resolution measurements required for the specular region. This method is also useful for calculating the effects of isolated sources (such as the sun) at angles away from the specular.

3.1.5 CCD Measurements.

To make a two-dimensional reflectance characterization of the screen (determining the relationship between (x,y) coordinates on the screen to incident and reflected angles), a CCD camera can be used (see Fig. 9). An annulus is placed in the center of the source to determine the specular reflectance and haze peak. Then a flat black plastic disk is placed directly onto the display such as to obfuscate the peak region from the detector. This reduces the veiling glare contribution and provides a measurement of the BRDF structure away from the peak.

4. HMD Metrology Standards

At present, no international standard exists that deals exclusively with the metrology of microdisplays. Standards may specify methodologies or instrumentation, but a document is needed that establishes good metrological procedures and provides diagnostics to evaluate them. The VESA Display Metrology committee plans to incorporate such information in the third version of its FPDM standard [7]. This would include not only measurements of display characteristics (brightness, uniformity, contrast, etc.) but also discussions on how well the display matches the eye system (convergence, accommodation, etc.). However, for many of these methods to be meaningful, the SED camera must improve contrast measurements by at least an order of magnitude.

5. Conclusion

Display metrology is not a simple matter. It is no longer adequate to think of only two types of reflection. Veiling glare must be minimized in order to make proper color and contrast measurements. Methods must be used that correctly indicate what the eye sees in near-eye displays. Further research at NIST on the SED and reflection metrology should address and to some degree simplify the complications associated with microdisplay measurements.

6. References


[7] The present version, Video Electronics Standards Association (VESA) Flat Panel Display Measurement Standard (FPDM), ver. 1.0 (May 1998) is available from VESA. Version 2, due out in early 2001, will expand to cover projection display metrology. The content of the third version will incorporate microdisplay metrology. This third version will be a cooperative effort of the VESA Display Metrology and Microdisplay committees.