1996 SID International Symposium

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PRINTED IN THE UNITED STATES OF AMERICA

Volume XXVII

ISSN 0097-966X

Library of Congress Card No. 75-642555

Editor: *Jay Morreale*
Palisades Institute for Research Services, Inc.

15.2: Specular and Diffuse Reflection Measurements of Electronic Displays

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Abstract

Display standards describe measurements of the diffuse and specular reflection coefficients. The adequacy of such procedures is compared with the bidirectional reflection distribution function (BRDF) measurements. Alternative methods are examined and their estimates of the specular and diffuse reflection coefficients are compared to the results of the BRDF measurement.

Introduction

Many display measurement standards seem to implicitly assume that the reflection from the display surface is a linear combination of specular and diffuse reflections. However, some surface treatments deliberately "smear" the specular reflections so as to make them less objectionable to the user. In this case, the total reflection from a display is no longer a simple combination of specular and diffuse reflection. Figure 1 shows the reflection from a flat panel display (FPD) on a portable computer (b) compared with the reflection from a strip of flat-black plastic (a) and a strip of gloss-black plastic (c) placed over the display. An integrating sphere with a 50 mm exit port is used to illuminate an area that included all three surfaces.

Using a photopic CCD (charge-coupled device) imaging system the luminance data from the three surfaces are shown in Fig. 2. The gloss-black plastic exhibits a sharp peak at the specular angle as expected. The flat black plastic exhibits the relatively uniform reflection characteristic of a diffuse surface. The reflection from the screen can be seen to not be described as a simple linear combination of diffuse and specular reflections.

The ultimate goal of this work is to be able to calculate the degradation of display performance (such as contrast metric) when the display is used in any ambient light arrangement based on simple reflection measurements made in a dark room. This work assumes that the reflection properties of the screen are the same regardless of whether the underlying pixel is on or off.

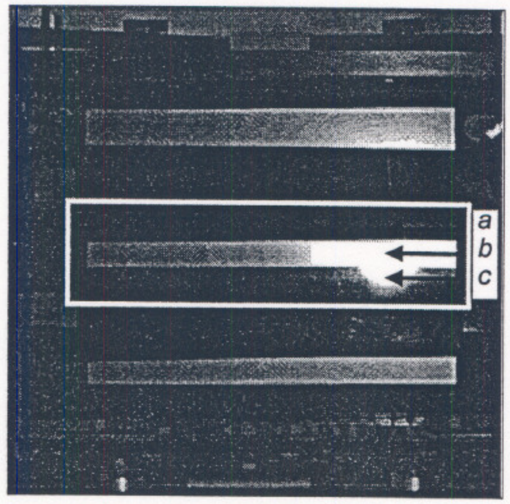

Fig. 1. Surface of FPD with flat black and gloss black samples. The white box is the area sampled, and the arrows locate lines of measured luminance.

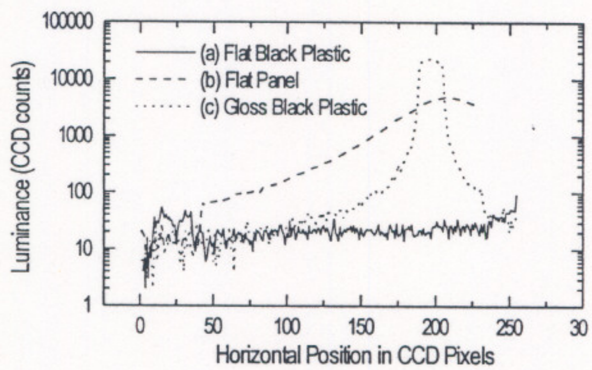

Fig. 2. Luminance profiles in Fig. 1.

Test of Proposed Reflectance Measurements

A standard under development [1] illuminates the surface of a display with two extended light sources with 150 mm apertures placed 500 mm from the display center at ±30° on either side of the surface normal (see Fig. 3). The display center, with or without a white diffuse reflectance standard in place, is measured from the normal. The diffuse reflectance coefficient q is defined as the ratio of the luminance to the illuminance:

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[1] *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] *Electricity Division, Electronics and Electrical Engineering Laboratory*

[3] *Optical Technology Division, Physics Laboratory*

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$$q = L/E \quad [sr^{-1}], \tag{1}$$

and is related to the diffuse reflectance $\rho_d \leq 1$ by $q = \rho_d/\pi$. When comparing against a known diffuse standard, the diffuse reflection coefficient is given by

$$q = q_W\, L/L_W \quad [sr^{-1}], \tag{2}$$

where q_W is the diffuse white reflectance coefficient of the standard, L is the diffusely reflected luminance of the display, and L_W is the diffusely reflected luminance from the standard. For a white standard with diffuse reflectance of $\rho_d = 0.98$, $q_W = 0.31\ sr^{-1}$.

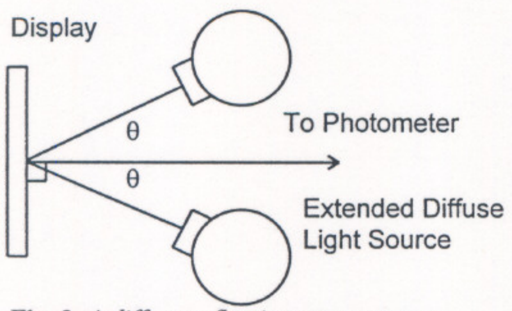

Fig. 3. A diffuse reflection measurement.

The diffuse reflection coefficient as defined is found to be a sensitive function of θ as shown in Fig. 4. If the surface of the display were a perfect Lambertian (diffuse) reflector, then we would expect a constant value for q as depicted by the dashed line in Fig. 4. (All luminance data in this paper are uncertain to ±10% with a coverage factor of k = 2. All angles are similarly uncertain to ±1° unless specified otherwise.)

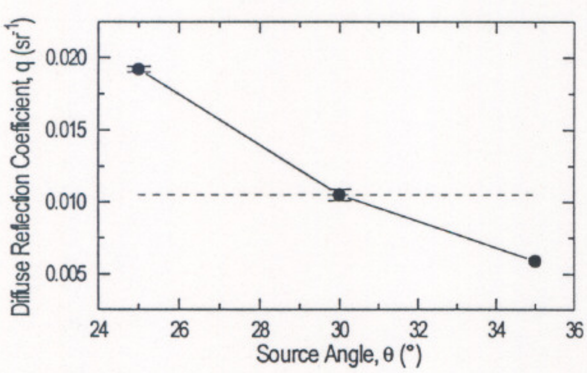

Fig. 4. *Diffuse reflection coefficient q versus angle of light sources θ.*

Another problem arises with the way some standards propose to measure and calculate the specular reflection coefficient. The specular reflection coefficient ρ_S is defined as

$$\rho_S = L_S/L_A, \tag{3}$$

where L_A is the luminance of the source, and L_S is the specularly reflected luminance obtained by subtracting a diffusely reflected luminance L_D from the measured luminance L_M:

$$\rho_S = (L_M - L_D)/L_A. \tag{4}$$

Here, L_D is calculated by multiplying the diffusely reflected luminance at 0° from the display by the ratio of the diffusely reflected luminance of the standard taken at 15° and 0°:

$$L_D = L_{D\text{-}0°}(L_{W\text{-}15°}/L_{W\text{-}0°}). \tag{5}$$

This model is correct only if the display exhibits a Lambertian diffuse reflectance, an assumption that this paper shows to be generally not true.

Another proposed method to characterize specular reflection is to use a small source of light. A light source with a 9 mm aperture is placed 500 mm from the display providing a 1° light aperture as viewed from the screen. A spot photometer with an aperture ≤0.3° is used to measure the peak. The peak of the reflection is shown in Fig. 5 for a region approximately ±0.3° about the peak. Within that narrow region the peak value can change from 30% to 40% making such spot measurements uncertain at best.

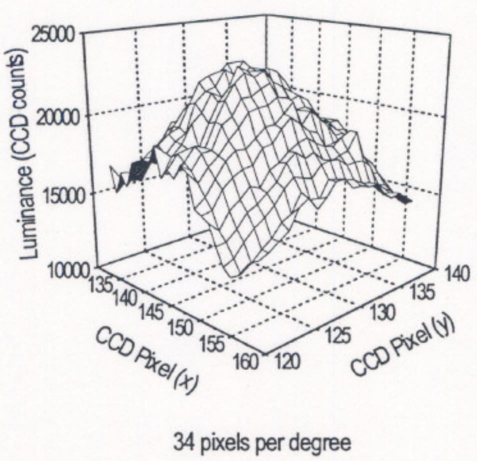

Fig. 5. *3D-plot of the reflection of the point light source from a flat panel display.*

The intermediate specular-diffuse nature of display reflection can even influence specular measurements from broad sources. An extended diffuse light source is placed 500 mm from the surface of a LCD flat panel display and at an angle of 15°. The measuring device is at the specular reflection angle of -15°. A series of apertures ranging from 150 mm to 50 mm in diameter in steps of 20 mm are placed in turn in front of the light source. Figure 6 shows the series of curves obtained from the spatial cross-section of the CCD images. As can be seen from these data, even at an aperture of 150 mm the reflected luminance from the display is not uniform (i.e., flat) in the center region and could therefore introduce errors in measurements of specular reflection. The area of quasi-uniform reflected luminance diminishes as the aperture of the light source is reduced. Therefore, the readings from any measuring device may depend on how accurately the device is aimed at the peak luminance and how much area is measured at the peak.

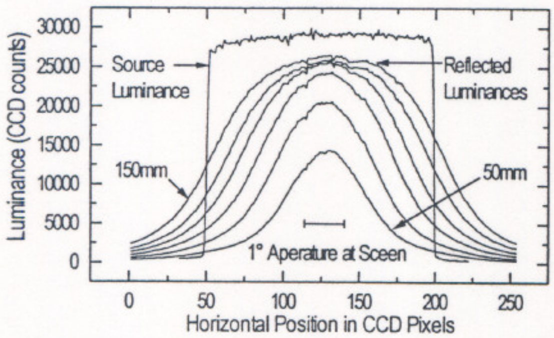

Fig. 6. Reflected luminance from a FPD using a diffuse light source with a variable aperture.

Another measurement standard [1] places the display in an integrating sphere with a photometer viewing the surface through a tubular light trap blackened on the inside. The tube reduces stray light from entering the photometer. A view of the test setup is given in Fig. 7. The maximum length of the tube is 1.25 m and the diameter is approximately 90 mm giving a minimum aperture of approximately 4°. The ratio of the luminance value of a LCD display L to that of the diffuse reflectance standard L_D is plotted in Fig. 8 as a function of tube distance from the screen. This ratio is presumed to be proportional to the diffuse reflectance coefficient of the display. If the display had a perfectly diffuse reflection component this ratio should have been a horizontal straight line. The dashed line is the luminance from the white standard which remains fairly uniform until the end of the tube is close to the display.

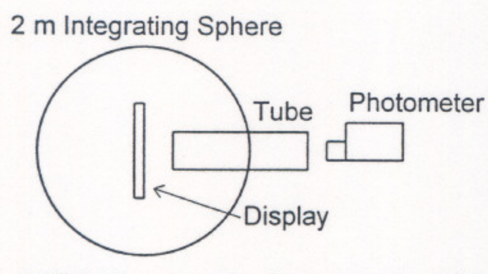

Fig. 7. Tubular apparatus for measuring reflectance from the interior of an integrating sphere.

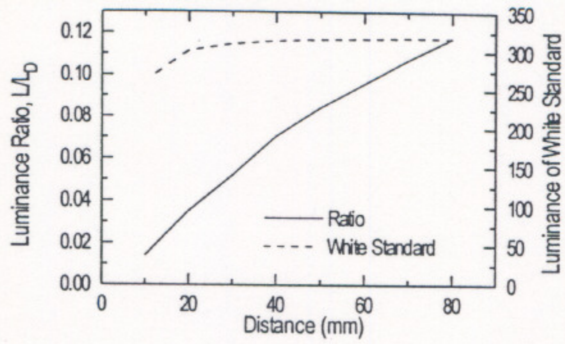

Fig. 8. Ratio of the reflected luminance from a FPD to the reflected luminance from a white standard versus distance of tube from surfaces.

BRDF Method

As is evident in the above discussion, reflection measurements of a display are complicated due to the fact that the reflectance properties of the surface of a display cannot be modeled by a simple combination of specular and diffuse reflection. There are a number of standard test methods for the measurement of gloss using goniophotometry. [2] However, a means to fully characterize the reflections from a surface is provided by the bidirectional reflection distribution function (BRDF). [3] Simply stated, an element of incident illuminance dE_i (corresponding to an element of solid angle $d\omega_i$) is related to an element of reflected luminance dL_r (correspondig to an element of solid angle $d\omega_r$) by the BRDF $f_r(\theta_i,\phi_i,\theta_r,\phi_r)$: [4]

$$dL_r = f_r(\theta_i,\phi_i,\theta_r,\phi_r)\, dE_i\,, \qquad (6)$$

where θ is the inclination angle from the normal, ϕ is the rotation about the normal, and the subscripts denote incident and reflected directions.

In practice, the BRDF is obtained for a sufficient number of incident and reflectance angles so that it can be adequately interpolated. The luminance can then be calculated for the illuminance distribution of the environment by integrating Eq. (6).

An example of two cross-sections of a BRDF is shown in Fig. 9 where a display surface is simulated by an anti-reflecting glass diffuser placed over gloss-black plastic. The peaked nature of the BRDF is what makes the surface suitable for display use. If the BRDF were

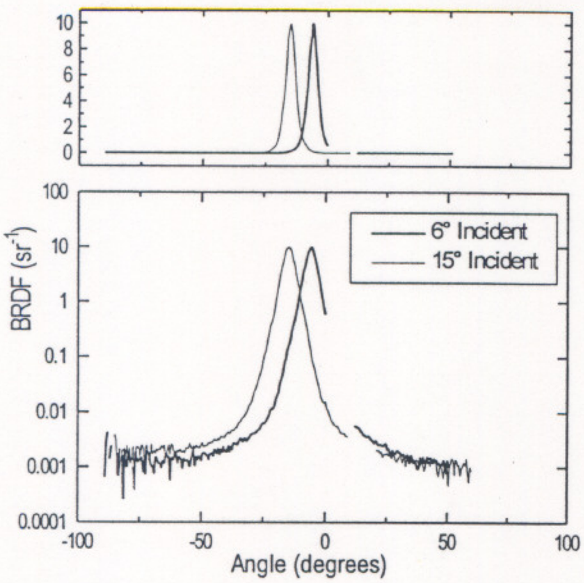

Fig. 9. BRDF for test sample with light source incident at 6° (thick line) and 15° (thin line) and the detector rotated. Both linear and logarithmic scales are provided for the same data. Incident and reflected axial angles are zero ($\phi_i = \phi_r = 0$) Gaps occur at aperture-detector conjunctions. Similar curves will be obtained with the detector and source interchanged. Instrumentation resolution is 0.6° for these data.

broad, the information displayed would be smeared or its contrast reduced remarkably since the plane of the display surface is often displaced slightly from the plane of the pixel surface. It is the continuous decrease in luminance with angle that makes reflection measurements difficult to simply characterize. If the BRDF does not level off and become flat for a range of angles, then a diffuse reflection measurement is not possible since the ratio of luminance to illuminance is never constant.

Attempts have been made to simply quantify the reflection properties intermediate between specular and diffuse. The CIE, Commission Internationale de L'eclarirage (International Commission on Illumination), has identified a metric which can indicate the sharpness of the BRDF. [5] The diffusion factor σ is defined to be the ratio of the mean of the luminance measured at 20° and 70° to the luminance measured at 5° from the normal using normally directed illumination:

$$\sigma = [L(20°) + L(70°)]/[2L(5°)]. \qquad (7)$$

For a perfect diffuse or Lambertian surface $\sigma = 1$. For the surface used for the BRDF in Fig. 9, $\sigma = 0.004$. For simple apparatus and the materials used for display surfaces, the reflected luminance at 70° can be small and difficult to measure (see Fig. 9). Further, metrics such as this only offer a characterization of the surface and do not permit a calculation of the display in all ambient environments.

Conclusion

Simple reflection meaurements appear unable to satisfy the requirement that we provide a reflection measurement which will enable the calculation of the display's performance in any ambient lighting condition. Although the use of the BRDF is adequate for such a calculation, obtaining the BRDF is not a simple exercise. Our initial hope to obtain a simple measurement of a display's reflection characteristics has not been realized because of the complicated structure of the reflectance of the display surface. Any methods which purport to measure the specular and diffuse reflection coefficients must be scrutinized to see if they properly account for the difficulties arising from reflections which fall in the intermediate regime between specular and diffuse.

References

[1] Since the standards examined for this paper are yet in a state of development and modification, we did not think it proper to directly associate any method with a certain standard. We have attempted to cast the proposed measurements in a generic fashion, the elements of which are found in many display standards which attempt to measure reflections.

[2] Annual Book of ASTM Standards, Section 6, volume 6.01, "Paint—Tests for Chemical, Physical, and Optical Properties; Appearance; Durability of Nonmetallic Materials."

[3] C. C. Asmail, C. L. Cromer, J. E. Proctor, and J. J. Hsia, "Instrumentation at the National Institute of Standards and Technology for Bidirectional Reflectance Distribution Function (BRDF) Measurements," SPIE Proc., Vol. 2260, pp. 52-61 (1994).

[4] F. E. Nicodemus, J. C. Richmond, J. J. Hsia, I. W. Ginsberg, and T. Limperis, "Geometrical Considerations and Nomenclature for Reflectance," NBS Monograph 160, October 1977.

[5] "Radiometric and Photometric Characteristics of Materials and their Measurement," C.I.E. Publication 38, C.I.E., Paris (1977).