24.2: Robustness of Display Reflectance Measurements: Comparison between BRDF and Hemispherical Diffuse Reflectance*

Seungkwan Kim
Division of Physical Metrology, KRISS, Daejeon, Korea

Edward F. Kelley and John Penczek
Optoelectronics Division, NIST, Boulder, Colorado, USA

Abstract

We measured in-plane bidirectional-reflectance-distribution-function (BRDF) profiles for specular, haze and Lambertian samples using a converging light beam and a photopic photodiode. The results were validated by comparing the hemispherical reflectance values calculated from BRDF data with direct measurements by the use of integrating spheres, whereby an agreement to within 2 % was achieved.

1. Introduction

Reflection properties of a flat panel display are important performance characteristics used to evaluate the display readability and viewing quality under certain illuminating conditions. [1] The bidirectional reflectance distribution function (BRDF) measurement provides a great deal of information about a display's reflection properties. In principle, we can determine the reflectance of an arbitrary display device for any type of illumination source-detector geometry if we have its BRDF data. [2] Therefore, the BRDF can be regarded as a fundamental metric in the determination of display reflectance. This paper demonstrates how the BRDFs of samples exhibiting a variety of scattering properties can be used to calculate the hemispherical diffuse reflectances of these samples.

The great utility of the BRDF data is tempered by the difficulty of the measurement. Intercomparisons between different BRDF systems are often difficult due to differences in detector signatures and the sensitivities to the measurement configurations. Given this difficulty, we propose to validate the system by a correlation to a direct reflection measurement at a specific source and detector geometry. In previous investigations on display reflectance measurements, we have determined that the hemispherical diffuse reflectance measurement performed with an integrating sphere is the most robust, reproducible and unambiguous direct measurement among the conventional methods used to characterize display reflection. [3]

In this paper, we present the measurement results obtained by use of a high-resolution in-plane BRDF apparatus and show the agreement of the hemispherical diffuse reflectance values calculated from the BRDF data with those measured by the use of integrating spheres. [4]

2. Measurement Apparatus

We constructed a high-resolution in-plane BRDF measurement apparatus with an array-type light emitting diode (LED) as a light source, a photodiode (PD) with a photopic filter (V_λ filter) as a detector, and two rotation stages, one for the sample and the other for the light source. Figure 1 shows a schematic of the apparatus.

Light from the LED was passed through a circular aperture with a diameter of approximately 2 mm. A lens is used to focus the light onto a detector aperture with a diameter of 5.04 mm ± 0.01 mm after being reflected by a test sample. The diameter of the specular image of the source aperture was made to be slightly less than the detector aperture.

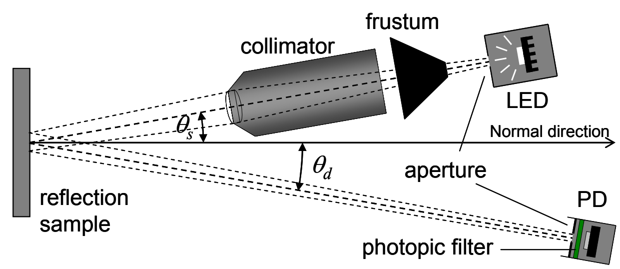

Figure 1. Schematic of the BRDF apparatus with a converging optical beam and a photopic photodiode detector.

We placed a frustum between the collimator and the LED source in order to prevent unnecessary stray light from entering the collimator, and the entire source apparatus was wrapped with black felt to reduce stray light in the room. The measurement results were acquired in a darkroom where all the surfaces nearby the apparatus were painted black or covered with black felt. The distance between the center of the reflection sample and the detector aperture was 150.0 cm ± 0.2 cm. The angular resolution was determined to be 0.19° for this configuration.

Photocurrent from the PD measured by a digital electrometer. was proportional to the luminous flux of the reflected beam entering the detector aperture. In order to determine the relative amount of incident luminous flux on the reflection sample, we first measured the photocurrent of a black glass reference of known specular reflectance. We calibrated the specular reflectance of the black glass with a separate measurement apparatus.

The relative luminous flux from the LED source was monitored by an additional PD located inside the collimator and near the lens. Any level change in the monitor PD photocurrent permitted corrections to be made in the incident luminous flux during the BRDF measurements.

BRDF is defined by the ratio of the luminance from the sample to the illuminance on the sample. Since it is a ratio, it can be expressed by the relative photocurrents as:

$$B(\theta_\mathrm{s}) = \frac{L_\mathrm{v}}{E_\mathrm{v}} = \frac{\zeta_\mathrm{b} J_\mathrm{s}}{J_\mathrm{b} \Omega_\mathrm{d} \cos\theta_\mathrm{d}} , \quad (1)$$

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where B is the BRDF in sr^{-1}, L_v is the luminance from the sample, E_v is the illuminance on the sample, ζ_b is the specular reflectance of the reference black glass, J_b is the photocurrent proportional to the luminance from the reference black glass, J_s is the photocurrent proportional to the luminance from the sample, Ω_d is the solid angle from the sample center to the detector aperture, θ_s is the source angle, and θ_d is the angle of the detector from the sample normal as shown in Figure 1. It is interesting to note that BRDF is not explicitly dependent upon θ_s. Its dependence upon θ_s comes through J_s. For these measurements, the detector angle θ_d was set to 5°, and we changed the source angle θ_s while taking measurements of the photocurrent J_s.

3. Experimental Results

3.1. BRDF Measurements

We measured the BRDF profiles of three reflection samples as a function of the incident angle θ_s starting from the specular direction at 5°. The first sample was designated as S, which was an ordinary black glass with a dominant specular reflection. The second sample was designated as H, where the haze component dominated. The third sample, designated as SHL, had specular, haze and Lambertian components simultaneously. All samples were 7.5 cm by 7.5 cm in size. The beam diameter at the specular direction was approximately 1.5 cm, and hence the measurement was taken up to 76° before the beam touched the sample edge.

The calibrated specular reflectance of a reference black glass was 0.04063 (relative expanded uncertainty of 0.2% or less with a coverage factor of two), and the photocurrent was approximately 200 nA when it was on the stage at the specular direction and the room lights were turned off. The background noise level was approximately 10^{-5} nA when the LED source was turned off.

When the reference black glass was replaced by the test sample, a slight angular readjustment was required to make the specularly reflected beam point through the detector aperture. For sample H, it was difficult to find the specular direction due to the absence of a distinct specular reflection. Hence, special care was taken in placing sample H so as not to change the angle at which we measured the photocurrent of the reference black glass.

Figure 2 shows BRDF profiles of the three samples. Sample S had the strongest peak in the specular direction and a relatively flat Lambertian-like scatter. The fluctuations in the BRDF appearing after 13° are due to a low signal-to-noise ratio. The other two samples showed rather stable BRDF profiles over all incidence angles because of the large amount of diffuse scatter compared to sample S. There were more than three orders of magnitude difference in BRDF values between the specular and diffuse scatter for sample S, with an order of magnitude for sample SHL and no noticeable difference for sample H. The diffuse scatter manifested by sample S is likely caused by imperfections in the sample (microscopic scratches and digs) as well as scattering within the source.

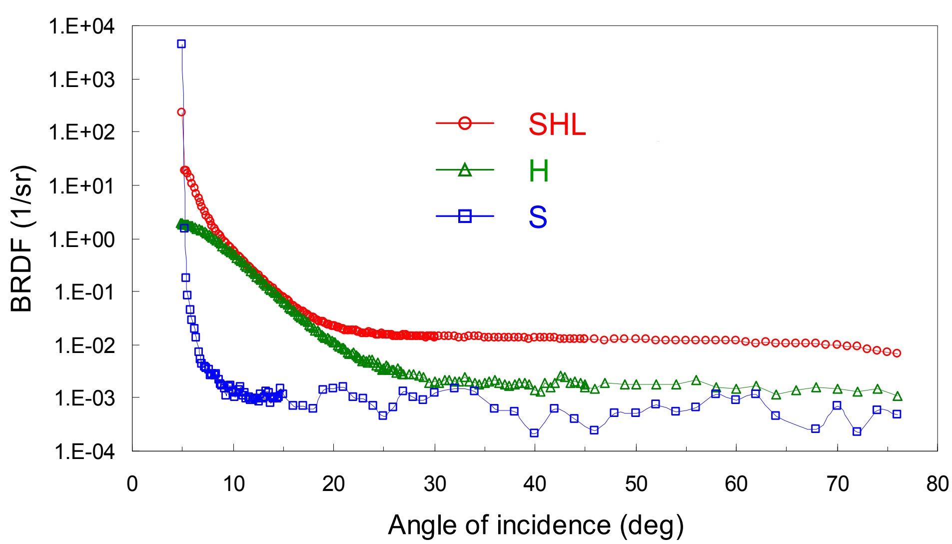

Figure 2. BRDF profiles of three reflection samples.

The samples had good rotational symmetry about the z-axis (normal to the sample surface), and there were no differences beyond reproducibility of approximately 0.5 % in BRDF values when it was rotated to different azimuthal angles. On this basis and arguments below, we would estimate the expanded relative uncertainty with a coverage factor of two for the BRDF measurements to be approximately 3 %.

3.2. Hemispherical Diffuse Reflectance

The BRDF measurement contains a great deal of information about the scatter properties of a sample. These data can be integrated to express conventional reflection metrics. In this case, we calculated the hemispherical diffuse reflectance of the three samples. We assumed that the sample is located at the center of the sphere and that the wall luminance of the sphere is uniform.

The hemispherical diffuse reflectance is given by:

$$\rho = \frac{\pi L}{E} = \zeta_s + 2\pi \int_0^{\pi/2} B_d(\theta) \sin\theta \cos\theta d\theta \, , \qquad (2)$$

where ζ_s is the specular reflectance of the sample and $B_d(\theta)$ is the diffuse component of the BRDF without the specular component.

The measured BRDF at 5° (specular direction) was then used as $B_d(\theta = 0)$ and so were the BRDF data at the angle θ_s, as $B_d(\theta = \theta_s - 5°)$. We set zero for the BRDF value at 90° and generated BRDF data at every 0.1° or 0.2° with a spline-interpolation method. We then numerically integrated the BRDF data with Simpson's 3/8 rule.

Table 1 summarizes the calculated results and includes the values of the hemispherical diffuse reflectance of the samples, which were measured directly by the use of integrating spheres. The measured values were the average obtained from three integrating spheres with diameters of 1.9 m, 0.90 m and 0.61 m. [4]

Table 1. Hemispherical reflectance values calculated by BRDF data and measured with integrating sphere.

Samples	BRDF			Integrating sphere	Deviation (%)
	Specular	Diffuse	Total		
S	0.0400	0.0023	0.0423	0.0422	0.42 %
H	0.0000	0.0485	0.0485	0.0479	1.2 %
SHL	0.0018	0.1132	0.1151	0.1154	-0.28 %

The agreement between the calculated and measured values is quite excellent considering that the relative uncertainty at the 95 % confidence level is estimated to be 1 % for the direct integrating-sphere method. [4]

In addition to the uncertainty of the hemispherical diffuse reflectance measured with the integrating spheres, the difference between the calculated and the measured values can be produced by the angular misalignment of the BRDF apparatus, error in numerical integration, photopic response differences in detectors used with the integrating-sphere apparatus and BRDF apparatus. The light source spectral difference can also affect the results, but the effect should be negligible because the samples are spectrally flat.

The results in Table 1 clearly show that the deviation of the calculated value from the directly measured value was less than ±0.5 % for samples S and SHL, while the sample H produced a deviation of more than 1 %. The reason for the relatively large deviation for sample H could be explained by the fact that there was no specular image at the detector aperture, and thus a slight angular misalignment might happen during replacement from the reference black glass to sample H. The angular misalignment could be readjusted for the other two samples because they produced specular images.

We estimated the angular misalignment for the sample H by measuring BRDF after changing the starting angle from –0.4° to 0.2°. The results demonstrated that an angular misalignment of 0.1° can bring about a change of 3 % in calculated reflectance, as shown in Figure 3. Consequently, accurate sample alignment is critical when measuring BRDF for reflection samples without specular reflection.

We also considered the potential error introduced in the numerical integration of the BRDF data. We compared four different numerical integration rules: Trapezoidal, Simpson's, Simpson's 3/8, and Bode's. For the samples H and SHL, the deviation between maximum and minimum values of reflectance for these samples less than 0.2 %, whereas it was as large as 0.8 % for sample S. In Figure 2, the BRDF profile of sample S changed much faster than that for the other two samples as a function of angle and hence the integrated value was more easily affected by different integration rules.

Another factor that can contribute an error in numerical integration is the interpolation of BRDF data between 71° and 90° in θ. The worst case is if we set all values to zero in this range and integrate the BRDF data only to 71°. In such a case, the calculated reflectance values were reduced by 0.25 %, 0.83 %, and 1.3 % for samples S, H, and SHL, respectively. It is obvious from Figure 1 that the reduction was larger for the sample with a higher Lambertian component in BRDF. Therefore, one can expect that the uncertainty caused by selecting different interpolation methods could affect the overall reflectance value by much less than 0.5 %.

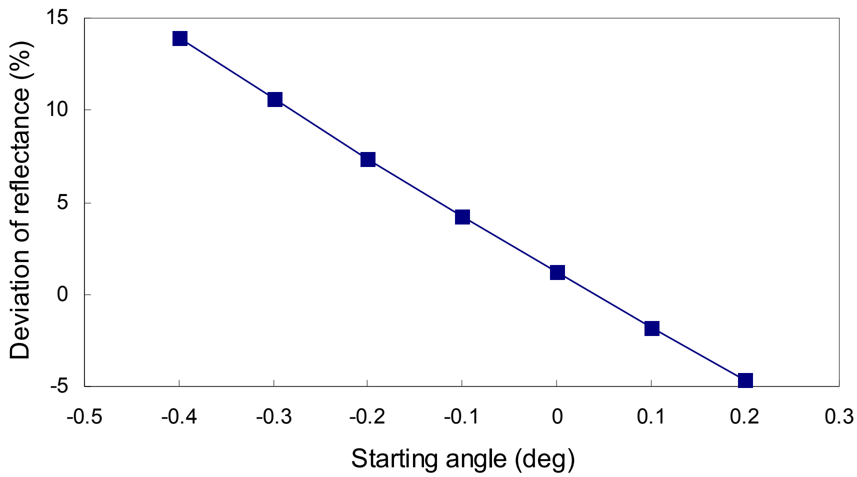

Figure 3. Deviation of reflectance for sample H as the starting angle is changed.

4. Conclusions

Three different types of reflection samples were measured with a high-resolution in-plane BRDF apparatus. We showed how BRDF data can be used to calculate conventional reflection metrics, such as hemispherical diffuse reflectance. We also successfully validated the BRDF measurements by comparing the calculated hemispherical diffuse reflectance values based upon the BRDF data with the directly measured reflectance values obtained by use of integrating spheres. This comparison demonstrates how a robust direct reflection measurement such as hemispherical diffuse reflectance can be used as an independent diagnostic to check the BRDF measurement system.

5. References

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