13.1: Measurement and Evaluation of Display Scattering

Michael E. Becker
Display-Metrology & Systems - D 76135 Karlsruhe - Germany

Abstract

A simple method is introduced for measurement and evaluation of light scattering of electronic displays. The method is based on the measurement of the lateral distribution of reflected luminance with an imaging detector and, after suitable transformation, it yields the characteristics of the BRDF of the sample with high resolution. The method is easy to implement and to carry out, since no directional scanning and painstaking alignments are required. This paper summarizes the basics of the approach, introduces an implementation and presents some typical results.

1. Introduction

Since the first proposals to apply the method of the *bidirectional reflectance distribution function* (BRDF) to characterization of light scattering from visual displays [1, 2], only limited amounts of BRDF-data from commercial displays (e. g. LCD-monitors) have been published. Measurement and evaluation of BRDF-data still requires either a mechanical system for motorized scanning of the viewing-directions (or source-directions alternatively) or a conoscopic system that can project a collimated beam of light through its front-lens on the sample while catching all rays reflected from the spot of measurement. Besides the substantial investments for such instrumentation, a weak spot of the method is the fact that BRDFs obtained with different systems can only be compared in a qualitative way up to now. That means that e. g. the shape of the bell-shaped haze curve can be compared to those from other samples with the same apparatus, but extraction of comparable numerical characteristics is still hardly possible, since theses characteristics (e. g. height of the specular peak on top of the haze) are subject to substantial changes with the source-receiver signature of the individual systems [1, 3]. Numerical deconvolution is required to put the results on a comparable common basis.

While high-resolution BRDF measurement and evaluation provides useful details about the directional reflectance of electronic display devices (height of specular peak on top of haze, directionality, diffraction effects, etc.) the ergonomic rating of displays only requires the knowledge of specular reflectance factors for two sizes of the source aperture (e.g. 1° and 15° according to ISO 13406-2) and specific angles of incidence for calculation of the reflected luminance under specified illumination conditions (diffuse and directional).

Measurement of the specular reflectance factor of electronic displays with a variable-aperture lightsource was introduced by Kubota in 1994 [4] and related to the concept of the BRDF in 2002 [5]. In this method a limitation arises from the fact that diffuse sources (based e.g. on integrating spheres) are used which are supposed to provide a uniform luminance distribution across the exit port. At the same time however, a large amount of the light flux is wasted into directions which do not contribute to the measurement and thus, the fraction of flux illuminating the measuring spot is quite low and noise problems arise for small source apertures. In addition to the decreasing signal to noise ratio also the alignment of the receiver system with respect to the specular direction becomes more difficult and even small deviations may cause large errors in the specular reflectance [6].

In order to provide the specular reflectance data over the required range with sufficient accuracy and robustness in combination with the detailed characteristics of high-resolution BRDF-data without mechanical scanning we introduce the following measurement approach:

- application of an imaging photometer instead of a spot-photometer,
- high-intensity small area source instead of a variable aperture source,
- numerical data-processing to obtain the BRDF,
- numerical integration over receiver aperture to obtain the specular reflectance factors r_{S1} and r_{S15} (ISO-13406).

2. The point-spread function (PSF)

A simple arrangement is often used for demonstration of the basic features of the BRDF: the reflections of a sufficiently small source (point-source) in a display screen. This pattern of reflected light is deceptive because it looks very much like the BRDF of the sample with the haze component fading out with increasing distance to the specular peak. A second closer look however suggests that this pattern cannot be the BRDF of the sample, because each spot on the sample surface is illuminated from a special direction and it reflects into another specific direction. The basic idea of the approach proposed here is to sample the reflectance from each spot on the sample, P(x, y) and to transform the reflectance values adequately to obtain the BRDF characteristics.

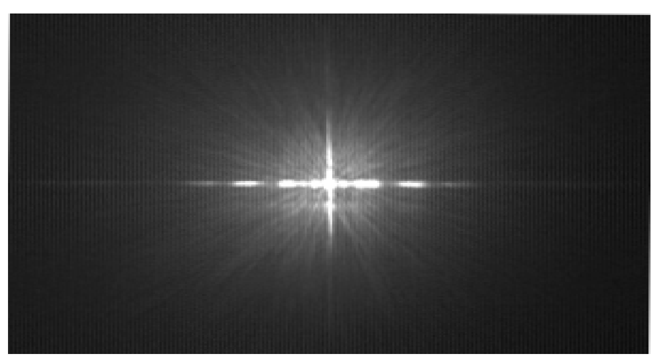

Figure 1: Luminance distribution obtained by reflection of a point-source in an LCD-monitor (PSF). X-axis horizontal, Y-axis vertical, origin placed in the center of the reflectance peak.

 ISSN/0004-0966X/04/3501-0184-$1.00+.00 © 2004 SID

3 Experimental

The setup for the measurement is sketched in fig. 2: a suitable isotropic light-source S and an imaging photometer (receiver) R, are placed within a plane perpendicular to the device under test (DUT) in a specular configuration, $\theta_S = \theta_R$. The distance of source and receiver from the DUT has to be adjusted to obtain the required aperture angle of the receiver and subtense angle of the source. The combination of these defines the source-receiver signature of the system, σ ($\sigma = \mathrm{atan}(r_S + r_R)/(d_S/\cos\theta_S + d_R/\cos\theta_R)$ with the radius of source and receiver aperture, r_S and r_R). Experimental evaluation of σ is carried out with a non-scattering front-surface mirror.

The distribution of light reflected from the area elements P(x, y) on the DUT is measured with an imaging photometer R and the data is evaluated to obtain the BRDF characteristics.

$$\mathrm{BRDF}(\theta(x, y), \phi(x, y)) = dL(x, y) / dE(x, y)$$

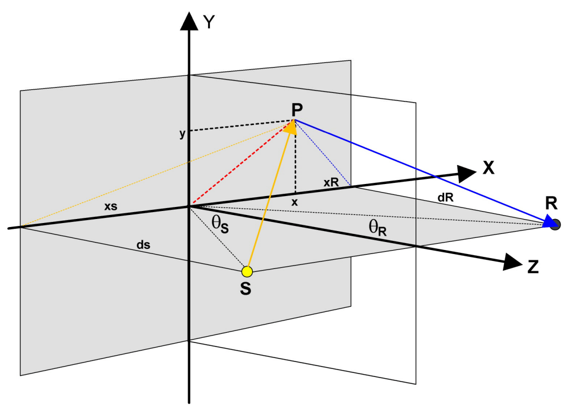

Figure 2: Measuring setup with isotropic lightsource S, imaging photometer (receiver) R, device under test DUT (in the XY-plane).

3.1 Geometry

For each spot P of the DUT in the XY-plane we obtain the *direction of light incidence* (from S to P) and the *direction of light reflected into the receiver* (from P to R) as follows:

$$\vec{r}_i = \overrightarrow{SP} = \begin{bmatrix}\theta_i \\ \phi_i\end{bmatrix} \ldots \text{with} \ldots \theta_i = \arctan\left(\frac{\sqrt{(x - x_S)^2 + y^2}}{d_S}\right) \tag{1a}$$

$$\phi_i = \arctan\left(\frac{y}{x - x_S}\right) \tag{1b}$$

$$\vec{r}_r = \overrightarrow{PR} = \begin{bmatrix}\theta_r \\ \phi_r\end{bmatrix} \ldots \text{with} \ldots \theta_r = \arctan\left(\frac{\sqrt{(x - x_R)^2 + y^2}}{d_R}\right) \tag{2a}$$

$$\phi_r = \arctan\left(\frac{y}{x - x_R}\right) \tag{2b}$$

In the symmetric case, $d_R = d_S$ and $\theta_R = \theta_S$, and for the spots P restricted to the X-axis, only the angles of inclination change (constant azimuth ϕ).

3.2 Measurement of the BRDF

In the standard arrangement for measuring the BRDF of a surface, an area element dA is illuminated from one direction, (θ_i, ϕ_i), and the reflected luminance is measured as a function of the receiver direction, (θ_r, ϕ_r).

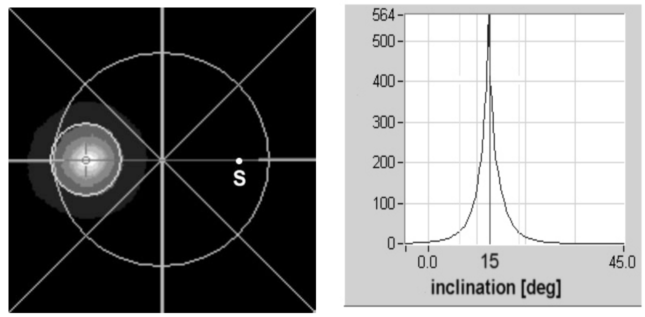

Figure 3: 2D-BRDF of an LCD-screen (left), $\theta_i = 15°$, source-location S, horizontal in-plane-BRDF (cross-section at $\phi = 180°$) (right). Conoscopic measurement, system-signature $\sigma \approx 1°$

In order to take a look at the geometrical conditions for measuring the BDRF we fix second coordinate system at the location of the receiver R with the z'-axis collinear with the specular direction, PR. The x and z-axis of the second coordinate system lie in the XZ-plane and the y'-axis is parallel to the Y-axis. The BRDF can be graphically represented by plotting the reflected luminance as a function of the angular distance of the reflected beam to the specular beam, θ^*, and of the angular difference between the azimuth of the reflected beam and the azimuth of the incident beam, ϕ^*.

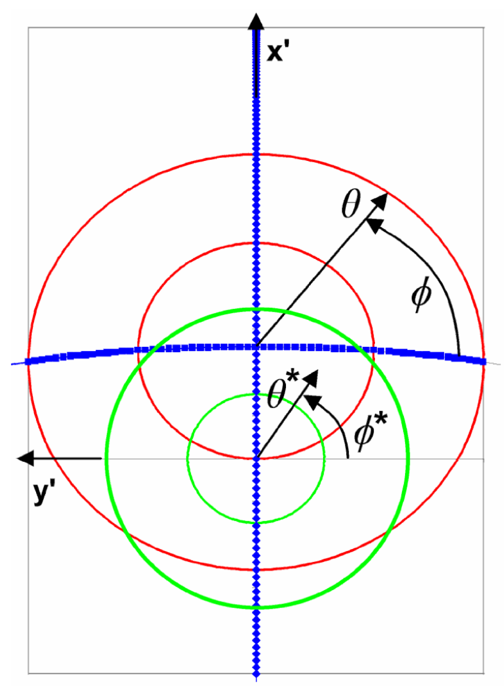

Figure 4: Loci for variations of θ (ϕ = 0°, 90°, 180° and, 270°), cross and for ϕ (θ = 15°, 30°), ellipses around center of the cross. Smaller circles indicate constant angle to the specular direction in the inclined coordinate system x', y', z' (with 15° inclination).

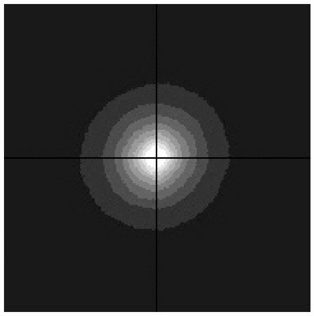

Figure 5: 2D-BRDF of the LCD-screen of fig. 3 centered about the specular direction, $(\theta_r, \phi_r) = (15°, 180°)$. The azimuth of light-incidence, θ_i is 0° (3:00 direction.).

Magnified view.

θ^* measured from the center,

ϕ^* measured from the 3:00 direction.

3.3 Transformation PSF to BRDF

For each pixel of the imaging photometer, $P_p(x', y')$, the location of the corresponding spot on the DUT, P(x, y), is computed and then, for each spot on the DUT the direction of light incidence and the direction of the beam reflected into the photometer is evaluated. For each pixel the angle between the reflected beam, PR and the specular beam at the same location, PS*, θ* is calculated. The second angle to describe the reflected beam is the azimuth of the intersection of the plane containing both the reflected and the specular beam with the plane of the DUT, ϕ*. This is done in analogy to the geometrical situation when measuring the BRDF.

$$\theta^* = \arccos\left(\frac{(x - x_S)\cdot(x_R - x) - y^2 + d_S \cdot d_R}{\sqrt{(x - x_S)^2 + y^2 + d_S^2}\cdot\sqrt{(x_R - x)^2 + y^2 + d_R^2}}\right) \tag{3a}$$

$$\phi^* = \arctan\left(\frac{y(1 + d_S / d_R)}{x - x_S - d_S / d_R \cdot (x_R - x)}\right) \tag{3b}$$

Plotting both angles θ* and ϕ* for each pixel of the photometer in a polar coordinate system we obtain the diagram shown in fig. 6. It is obvious, that the columns are transformed basically into vertical lines while the pixel-rows of the photometer array are transformed into basically horizontal lines.

A consequence of this simple transformation is, that we actually see the BRDF when looking at the PSF with the polar coordinate system centered about the specular direction.

In the next step, the intensities of the PSF as recorded with the imaging photometer (see fig. 1) are re-arranged and plotted into a polar coordinate system to obtain a representation as shown in fig. 5.

The in-plane BRDF is obtained from the PSF when y is set to zero in formula 3a.

4 Discussion

The approach of deriving BRDF characteristics of LCD-screens from the PSF is obvious to everyone observing the reflections of small light sources in display devices with bare eyes for a first qualitative judgement of the components of the BRDF. The general idea is mentioned in e. g. [7], but no details of the method and its implementation nor results have been presented and published so far.

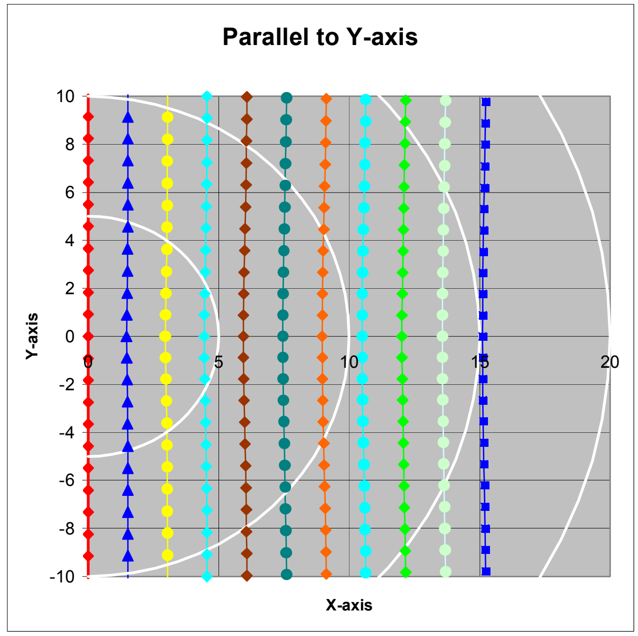

Figure 6: Loci of lines parallel to the Y-axis of the photometer array (only positive half shown here), in a polar coordinate system for $d_R = d_S = 650$ mm and $\theta_R = \theta_S = 15°$. The maximum angle of inclination covered in this measurement is 15° (in the XZ-plane). Concentric circles for θ* = 5°, 10°, 15° and 20°. Maximum angle of light incidence is 22°.

The transformation from the PSF to the BRDF as introduced here maps the angles of inclination relative to the specular direction, and the azimuth-angles relative to the incident beam not taking into account their absolute values. This can be done as long as the BRDF is sufficiently constant with respect to variations of the specular angle. The variation of the features of the BRDF with angle of inclination has been analyzed by E. F. Kelley e. a. [8] and it has been shown, that the characteristics (i. e. peak value and shape) remain fairly constant over an extended range of incident angles (e.g. 3° to 30°). Visual observation of the PSF under various angles of light incidence also confirms the stability of the reflected pattern. The reflective properties of the DUT must be sufficiently constant over the area included in the measurement.

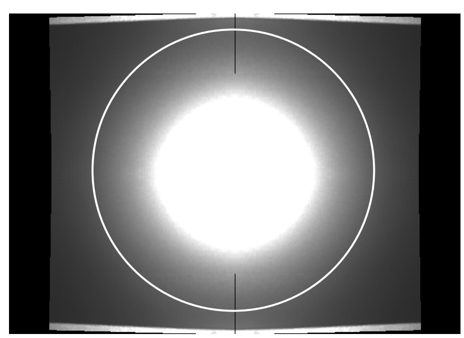

Figure 7: BRDF obtained by transformation of the PSF with circle for θ* = 15°

Further considerations and measures for the transformation:

- Symmetry considerations are used for widening the range of inclinations θ* in one measurement without loss of resolution (transformation of one quadrant only).
- Numerical correction for the non-uniformity of illuminance (from $\cos^3\theta$ to $\cos^4\theta$) over the area of measurement is used.

After transformation of the PSF into the 2-dimensional BRDF the reflectance factors r_{S1}, r_{S15} according to Kubota (ISO 13406-2) can be obtained via the concept of the inverse-BRDF (application of the Helmholtz reciprocity). While in the setup of Kubota the source aperture is varied, the same results can be obtained with a constant small source and a variable receiver aperture which is realized by integration over the BDRF.

5 Results

Figure 7 shows the 2D-BRDF of the sample of fig. 3 (BRDF measured conoscopically) as obtained from the PSF. The contours of the region of transformation (originally a rectangular grid) is slightly distorted in the same way as indicated in fig. 6.

Figure 8 shows the IP-BRDF of the sample of fig. 4 obtained from the PSF. This measurement obviously has a higher resolution (i. e. smaller source-receiver signature) than the results of fig. 4 and the specular peak on top of the haze can clearly be identified and separated from the haze. The FWHM of the specular peak in fig. 8 is 0.2°.

6 Conclusion

The presented method establishes the relation between the PSF and the BRDF of flat samples and shows how a small-aperture imaging photometer can be used for evaluation of 2D-BRDF features with minimum efforts and instrumentation. Evaluation of characteristics for ergonomic rating of displays is thus made easy.

7. References

[1] M. E. Becker: "Evaluation and Characterization of Display Reflectance", SID '97 Digest, pp. 827

[2] E. F. Kelley, G. R. Jones: “Utilizing the BRDF to predict reflections from FPDs”, SID ’97 Digest, pp. 831

[3] John C. Stover: "Optical Scattering, Measurement and Analysis", SPIE 1995

[4] S. Kubota: “Measurement of specular reflectance of LCDs”, Proc. Int. Symp. Illum. Engineering Soc. Jpn., (1994), pp. 241

[5] M. E. Becker: "Measurement of Display Scattering", Proceedings of the 22nd IDRC 2002, pp. 803

[6] E. F. Kelley: "Sensitivity of Display Reflection Measurements to Apparatus Geometry", SID'02 Digest, pp. 140

[7] E. F. Kelley: "FPD Measurements and Standards", SID Application Tutorials 2001, slide no. 79

[8] E. F. Kelley, e. a. : "Display Reflectance Model Based on the BRDF", Displays, Vol. 19, No. 1, June 30, 1998, pp. 27-34 (June 1998) - BRDFs for 3°, 10°, 20° and 30°

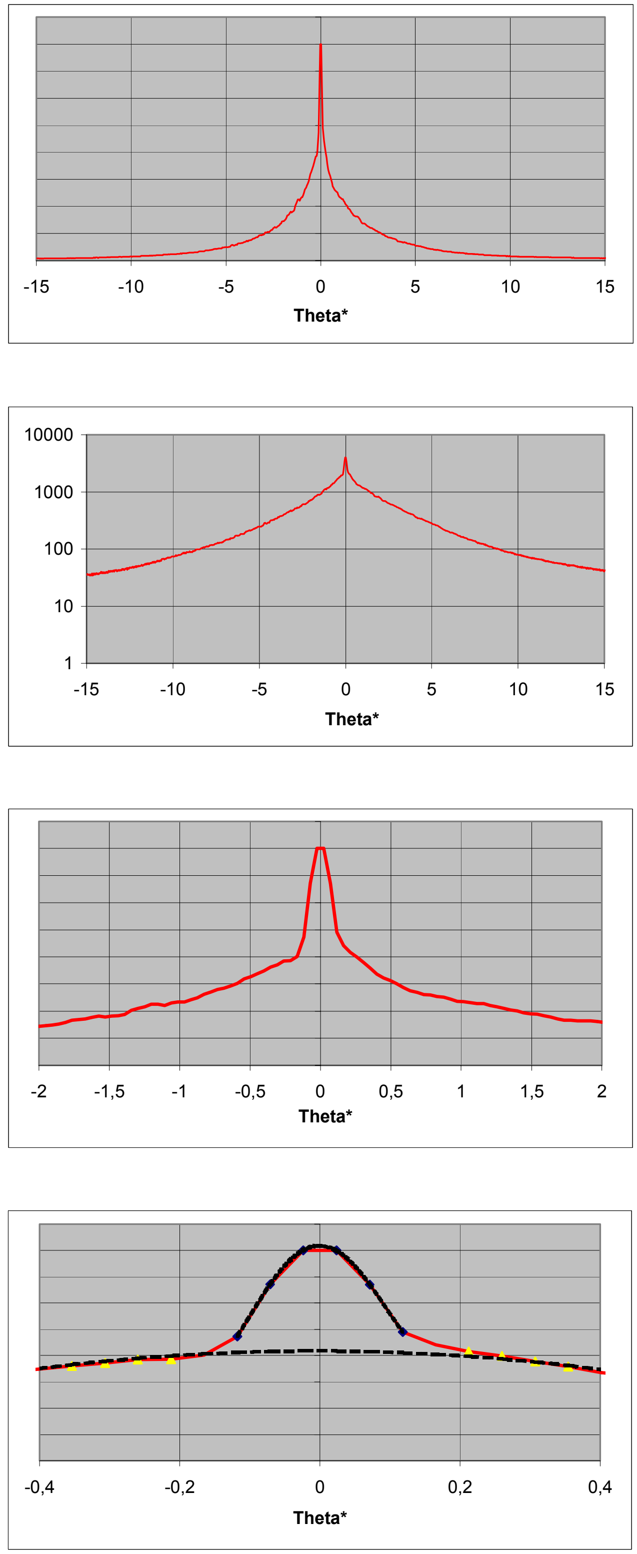

Figure 8: IP-BRDF from the PSF of the sample of fig. 3 with different scalings, θ_S = 15°. Fitting of two parabolas for separation of specular peak from haze hill (bottom).