

P-109: Measurement of Display Scattering

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Abstract

We present a simple method for measurement and evaluation of light scattering as needed for rating of the ergonomic performance of electronic visual displays. The method does not require directional scanning and it provides the specular reflectance of the sample as a function of the source aperture. This approach can be realized with normal spot-photometers and with imaging photometers, the source for illumination of the sample under measurement is simple and inexpensive and the BRDF of the sample can be reconstructed.

1. Introduction

Every user of electronic visual displays (e.g. computer monitors) may be familiar with the highly disturbing effect of ambient light sources that are reflected by the display. These unwanted reflections, called *glare*, reduce the contrast of the displayed information and, if an image of the light source is visible via reflection, the eyes of the observer are stimulated to repeatedly change focus between the display surface (i.e. the layer where the visual information is generated, e.g. the phosphor layer in CRTs) and the more distant image of the light source, thus often causing visual fatigue, headache and other negative effects in the observer. These negative effects of glare can be significantly reduced by the application of scattering anti-glare layers on the upper display surface. Besides reduction of the light intensity that is reflected into the eyes of the observer, also the lateral distribution of the displayed information (image resolution, contrast) may be negatively affected by scattering.

Measurement and evaluation of the light reflected and scattered by flat panel displays in terms of the *bidirectional reflectance distribution function* (BRDF) has been described by several authors in 1997 [1, 2]. As early as 1994, Nuijs and Horikx presented their extensive analysis of "diffraction and scattering of antiglare layers" for CRTs characterizing them via "angle resolved scattering" [3]. The BRDF approach, if adequately applied to translucent multilayer stacks [4], provides the complete characterization of the light reflected from a display as a function of the following parameters:

- ◆ direction of light incidence (source) and observer (receiver),
- ◆ wavelength of light and state of polarization,
- ◆ state of electrical driving.

This method however may produce prohibitively large amounts of data, it is based on usually expensive instrumentation with mechanical or optical scanning [1].

Moreover, there is still one intrinsic problem, which makes comparison of BRDF data evaluated with different devices (i.e. reproducibility) impossible whenever the *source-receiver signatures* of the devices are not identical. That implies that for the time being BRDF-curves certainly do provide us with an idea about the contributions of the three basic components of reflection (i.e.

specular, haze and Lambertian), but re-evaluation with a different measuring system will yield different numerical results in most cases (e.g. height of the specular spike on top of the haze-peak).

In order to make reflectance evaluation as required for rating of the ergonomic performance of displays (e.g. ISO 13406) more feasible and available to a large number of metrologists and laboratories, we are proposing a method that does not require expensive equipment for directional scanning while still providing characteristic results and the required robustness. Even though no directional scanning is involved, the method provides information about the BRDF of the sample. This method has been originally proposed by Kubota [5] for evaluation of the ergonomic aspects of glare caused by light sources of various sizes.

2. Glare reduction by scattering

The reduction of unwanted but apparent contrast by reflection of ambient light sources can be minimized by the application of a *scattering anti-glare layer* on the front-surface of the display. Such a scattering layer does not only reduce the flux reflected at the outer surface of the display but at the same time it reduces the "distinctness" of the displayed information. This requires a careful optimization of the scattering properties in order to obtain a solution that satisfies both conditions: sufficient reduction of *glare* while maintaining the *distinctness of image* [6] as described in [3].

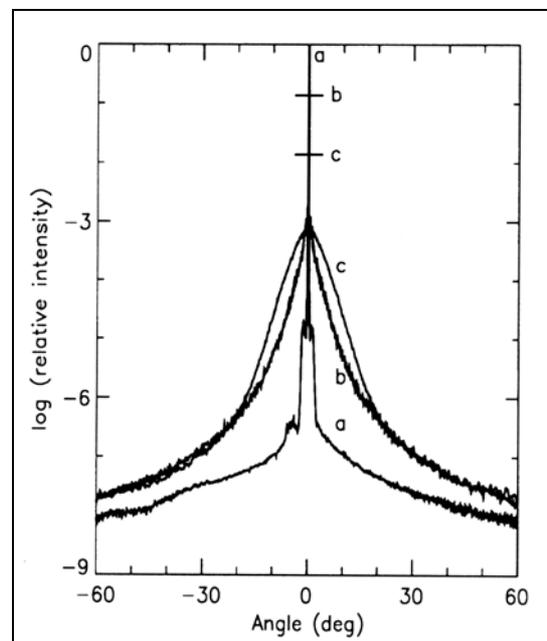


Figure 1: High-resolution BRDF (intensity of scattered light versus angle of receiver inclination) for (a) polished glass, (b) anti-glare coating and (c) etched glass surface according to [3]. The source-receiver signature of the apparatus is 0.143° .

Figure 1 shows the BRDF-curves (resolution of 0.143°) of a polished glass surface (a), and the same surface coated with two different anti-glare layers (b, c) as measured by Nuijs and Horikx [3]. The maximum value of the intensity axis corresponds to the flux reflected by the polished non-scattering glass surface which depends on the angle of light incidence and the refractive index of the glass and is given by Fresnel's formulas.

The intensity of reflected light forms a "spike" around the angle of light incidence (i.e. specular angle) and it sharply drops for receiver directions that are off-specular to levels of 10^{-5} . The "structures" that can be seen in the BRDF of curve (a) at intensities of 10^{-5} and 10^{-7} are artifacts caused by the apparatus. The scattering of the anti-glare treated surfaces gradually goes down to levels in the range of 10^{-8} for receiver inclinations of 60° while imperfections of the polished surface are causing the gentle slopes of BRDF-curve a.

It is apparent how much the reflection in the specular direction is reduced by scattering of the incident flux into directions that are close to specular. Depending on the geometrical details of the scattering structure, the bell-shaped curve below the specular spike, called *haze*, can have different characteristics (compare curve b and c). Table 1 shows that reflections in the specular direction can be reduced by scattering to 0.014 of the reflection of the uncoated glass.

Sample	Gloss (ASTM)	Spec. Reflectance compared to glass	curve
polished glass	100	1	a
AG coating	69	0.139	b
etched surface	69	0.014	c

Table 1: Reduction of specular reflections by scattering (after [3])

A surface with ideal scattering properties (ideal diffuser, Lambertian surface) would be represented in the BRDF-representation of Fig. 1 by a straight horizontal line. The level of this line is determined by the solid angle subtended by the aperture of the receiver, Ω_R .

The directional resolution of a setup for measuring the BRDF is called *source-receiver signature* because it is typical for a specific combination of source and receiver. Its shape and size are determined by the angular size of the light-source and the acceptance cone of the receiver, Ω_R [1].

3. BRDF measurement and evaluation

Measurement of BRDF in its original version is limited to non-transparent (opaque) surfaces with the receiver field-of-view completely enclosing the illuminated area on the sample surface. Electronic displays however are usually composed of several at least translucent layers. This special structure of the objects of measurement considered here requires a modification of the method in order to exclude errors caused by multiple partial reflections from various optical interfaces inside the display [4].

Two source configurations can be used for correct BRDF-evaluation of multilayer stacks:

- ◆ Source producing a large diameter collimated beam with uniform intensity across the beam. Such a source can be realized e.g. with a small diameter light fiber and a lens. Lateral as well as angular intensity distribution of the light emerging from the fiber must be uniform for generation of a collimated beam with uniform intensity across the beam.
- ◆ Point source with sufficiently multidirectional emission to ensure uniform illumination in the vicinity of the measuring spot. Such a source can be realized with a high-intensity incandescent lamp with small filament. Angular source dimensions below 0.1° can easily be obtained this way.

There are basically two choices for directional scanning:

- Fixed source with scanning receiver (standard case),
- Fixed receiver with scanned source (useful for evaluation of visual displays, see [2]).

Directional scanning can be realized with a mechanical setup or alternatively with an optical system [7] where some problems are related to the generation of a collimated beam with low divergence. The BRDF in the most general case thus is a function of both the direction of light incidence and receiver direction, both specified by e.g. two polar angles. When only the angle of inclination is varied in the measurement with the receiver located in the plane of light incidence, we have the special case of "in-plane BRDF" which neglects all variations with the azimuth-angle but is easier to realize.

The conventional BRDF shows the directional distribution of the light reflected by the sample for a fixed small source as detected with a small-aperture receiver. However, we can as well reverse the direction of light propagation and keep the receiver fixed while a small source is moved around to vary the direction of light incidence. The BRDF-curves obtained under such "reversed conditions" would be identical to the curves measured in the original case.

This implies that every scattering surface not only scatters an incoming beam into a range of directions but it also collects light from the same range of directions and re-directs it into the receiver. This collection and redirection of light is illustrated by the visual appearance of a perfect Lambertian sample (well approximated by photocopy paper) which is perceived as "bright" from all directions because it collects light incident from any direction and redirects parts thereof into the observers eyes. A mirror without scattering does not effect such a re-direction of the light-rays since only specular beams are "transmitted".

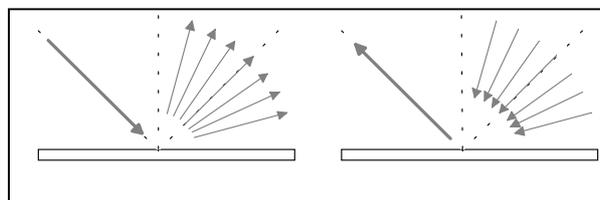


Figure 2: Scattering of a light-beam into a multitude of directions (left), collection of light-beams from a multitude of directions

4. BRDF of LCD-screens

We have measured the IP-BRDF of a variety of LCD-screens of notebook computers as shown in Fig. 3. The front-surfaces of all screens are coated with a scattering anti-glare layer. The multidirectional white-light source with an angle of inclination of 20° subtends an angle of 1° (seen from the sample). The steep curve peaked about 20° is the source measured via a non-scattering surface mirror (polished black glass) with a specular reflectance of 5% (normal air-glass interface). This curve represents the source-receiver signature with a FWHM of 1° . Reduction of reflections in the specular direction up to two orders is possible as can be seen by comparison of the BRDF of the black glass ($R_s = 5\%$) with the peak-value of the BRDF-curves of the LCD-screens.

In comparison to the BRDF-curves of Fig. 1 no narrow specular spikes are visible here, since the source-receiver signature of this setup of approx. 1° is too large to resolve those spikes. Convolution of the data shown in Fig.1 with a top-hat profile of 1° (corresponding to the source-receiver signature) width would produce similar curves without specular spikes as shown in Fig. 3.

The vicinity of the measuring spot on the sample and the spot itself are not illuminated by the source in a uniform way, since the distance from the source varies with distance from the center of the measuring spot. Depending on the emission characteristics of the source ($I = \text{constant}$ or $I = c \cdot \cos(\theta)$) the illuminance dE of an area element in the surface plane of the DUT varies proportional to $\cos^3(\theta)$ or $\cos^4(\theta)$ with θ centered about 15° in our experiments. When the distance between the source and the measuring spot is sufficiently large, the effect of non-uniform illumination can be neglected.

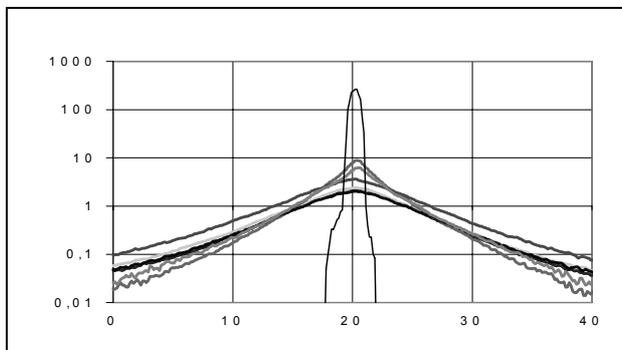


Figure 3: In-plane BRDF-curves of variety of notebook computer screens measured with a small multidirectional source (1° width) with an angle of inclination of 20° . The steep curve peaked about 20° is the source measured via a non-scattering surface mirror (polished black glass) with a specular reflectance of 5%. This curve represents the source-receiver signature with a FWHM of 1° . Reduction of reflections in the specular direction up to two orders is possible.

5. Variable aperture source method

In order to evaluate the scattering characteristics of display screens without directional scanning we have re-examined a method originally introduced by Kubota [5]. This method is based on the measurement of the reflected luminance with a spot photometer

with a fixed small acceptance angle and a uniform light source with variable aperture (e.g. between 1° and 15° measured from the sample). Variable aperture diffuse sources can be realized with integrating spheres (boxes), the exit port luminance requires calibration for each aperture size. The photometer is focused on the aperture plane of the source and the measuring spot is smaller than the smallest source aperture. Angle of light incidence and receiver inclination is set to 15° .

First, the luminance of the source is measured for all apertures since the luminance of the exit port usually varies with aperture. In the next step the luminance of the source is measured via a mirror made e.g. from polished black glass with the focus of the photometer set on the plane of the source. During these measurements it has to be assured that the measuring spot remains well centered in the source aperture. The quotient of the source luminance measured directly and via the mirror yields the *specular reflectance* of the mirror which must remain independent of the source aperture since no scattering is involved.

In the next step the mirror is replaced by a perfect diffuser with known diffuse reflectance ρ_D while keeping all other conditions unchanged. With the flux incident on the diffuser being evenly scattered into all directions, the intensity measured by the receiver should increase in a linear way with the solid-angle of receiver acceptance, Ω_R . The same applies when the direction of the light is reversed, i.e. the receiver aperture is kept constant while the source aperture is increased. Also in this case the flux received in the specular direction must increase in a linear way with the source aperture Ω_S if the measuring setup is performing correctly, i.e. $R_s(\text{Lambert}) = c \cdot \Omega_S$.

The specular reflectance R_s of the sample is measured as a function of the solid angle subtended by the source aperture Ω_S as shown in Figure 3. A flat non-scattering sample exhibits the same specular reflectance for all values of the source aperture (horizontal line with circles) while an ideal Lambertian reflector shows a linear dependence of reflectance with source aperture (straight oblique line with diamonds) caused by a linear increase of sample illuminance. Any other scattering sample yields a curve with a steepness smaller than that of the Lambertian sample. The quotient of flux reflected in the specular direction by the non-scattering sample and that of the Lambertian sample is inversely proportional to the solid angle subtended by the receiver aperture, Ω_R .

All samples, no matter which BRDF-curves their scattering produces, are located between the two extreme cases of a specular mirror and an ideal Lambertian diffuser in the RS/SA diagram.

Decreasing steepness with increasing source aperture in the RS/SA diagram indicates that most of the light is scattered into (collected from) the vicinity of the specular direction and further increase of the source aperture does not contribute to scattering in the direction of the receiver. A typical example is that of a semi-gloss standard made from etched black glass (dashed curve with squares in Fig. 4).

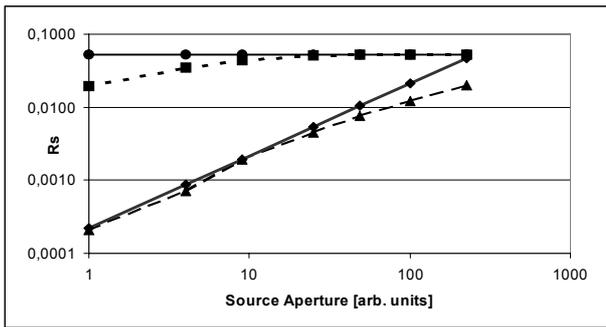
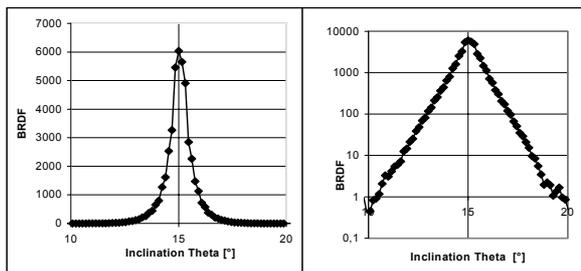


Figure 4: Specular reflectance R_s versus solid angle of source aperture Ω_s , SR/SA for a non-scattering sample (horizontal line with circles), a slightly scattering sample (curve with squares), an anti-glare coated LCD-screen (curve with triangles) and a Lambertian reflectance standard with $\rho_D = 98\%$ (straight line with diamonds). The data points are measured for 1° , 2° , 3° , 5° , 7° , 10° and 15° source aperture. Light incidence at 15° from normal.

The in-plane BRDF-curve obtained from the semi-gloss standard is shown in Fig. 5.

Figure 5: BRDF of the semi-gloss standard made from etched



black glass corresponding to the curve with squares in Fig. 4. Linear (left) and logarithmic scaling. The contribution from light propagating outside $\pm 5^\circ$ from specular is less than 10^{-4} of the peak value.

The different shapes of the SR/SA-curves can be obtained and explained by convolution of the respective BRDF-curve with a variable source diameter and plotting versus the solid angle of the source aperture. It is then comprehensible that the Lambertian plateau results in an oblique straight line ($L_r = \rho_D / \pi * L_s * (\pi * r_s^2)$), the non-scattering mirror yields a horizontal line and the semi-gloss standard results in a curve with decreasing gradient (curve with squares in Fig. 4). A smaller receiver aperture Ω_R would shift the curve of the Lambertian reflector in Fig. 4 to lower values for R_s while maintaining the gradient.

6. Discussion

The variable source aperture method described here provides information about the BRDF of the sample without directional scanning. It should not be confused however with a similar method based on a variable aperture source recently introduced by Kelley [8]. This method uses source apertures below 1° in order to

evaluate the height of the specular spike located on top of the haze peak.

All results of the VAS-method are confined between two extreme cases: the non-scattering mirror and the ideal diffuser. Both samples can also be used for checking the proper performance of the measuring setup.

Specular spikes obvious in the high-resolution BRDF of anti-glare layers as shown in Fig. 1 cannot be resolved with the VAS-method because of the large source-receiver signature in the range of 1° . Alternatively, the distinctness-of-image can be determined according to ASTM 430 or by projection of suitable resolution targets [4].

7. Conclusion

This is the first time that the scattering-evaluation method of Kubota has been related to the scattering properties of the samples characterized by BRDF evaluations. Even without directional scanning of the light reflected by the sample the basic shape of the sample BRDF can be obtained by deconvolution.

Analysis of the SR/SA-curves yields the most important scattering characteristics as needed for e.g. rating of the ergonomic performance:

- specular reflectance R_s for a range of source apertures that are relevant for the rating of the ergonomic performance of electronic display devices according to [4] and ISO 13406,
- shape of BRDF from the slope of the SR/SA-curve (purely specular samples with a pulse-shaped BRDF yield a straight horizontal line with zero gradient, ideal Lambertian diffusers yield a linear curve with the maximum possible steepness).

The measurements and evaluations can be carried out in a fixed setup with conventional spot-photometers (with reduced aperture angle) and alternatively with imaging photometers. The light source for illumination of the sample is simple and easy to realize.

8. References

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