# Display Reflectance: Clearing the Haze

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**ABSTRACT**

*Analysis of the point-spread function (PSF) yields the directional variations of display reflectance with high resolution in the vicinity of the specular direction and now - at reduced resolution - also at off-specular directions, thus providing a data basis for determination of a set of complete in-plane BRDFs/BTDFs. This approach is applied to identification and separation of mirror, haze and Lambertian reflection components which can be classified into such components that are forwarding visual information to the observer (*i. e. the *visual signal) and disturbing reflections (*i.e. *visual noise).*

## 1 Introduction

In order to assure recognition of visual information provided by display screens under ambient illumination, disturbing, annoying and disabling reflections (glare) have to be controlled. Scattering anti-glare (AG) layers are and have been extensively used for control of reflections, but unfortunately these layers in combination with the display subpixel matrix, often generate a disturbing visual phenomenon named *sparkle*, a kind of a random moiré pattern [1, 2]. Sparkle is perceived by the human observer as a random arrangement of tiny dark spots across the display area with the pattern changing its appearance rapidly with viewing direction.

The light from the display subpixels which is forwarding the intended visual information (signal) to the observer is scattered during transmission through the AG-layer and as a consequence, images and text may be blurred and details may be lost if the overall system performance has not been adjusted appropriately [3].

In order to optimize the visual performance of advanced displays committed expert engineers should carry out the following optimization:

- minimization of unwanted reflections;
- minimization of disturbing sparkle; and
- minimization of blurring of images and text.

Unfortunately, a local minimum of one of these quantities (e.g. reflection) may be resulting in a local maximum of another quantity (e.g. sparkle or image blur).

A prerequisite for such a demanding optimization is the availability of robust measurement methods and instrumentation for reliable and time-saving acquisition of the above listed optical characteristics.

## 2 Measurement of directional variations

The most comprehensive characterization of the directional distribution of scattered reflected and transmitted light is given by the BSDF (*bidirectional scattering distribution function*) [4]. The BSDF is a function of the direction of incident and received radiation, of wavelength and polarization state of the light. Measurement of the BSDF requires either

- motorized directional scanning mechanisms;
- complex lens and/or mirror systems, or, alternatively,
- analysis of the lateral distribution of scattered light, i.e. the spread-function of point or line light sources as first mentioned in [5].

The latter approach, due to its simplicity and the modest instrumental efforts involved, is well suited for industrial use and established for characterization of the scattering characteristics of anti-glare (AG) layers for display devices. That method does not require motorized directional scanning and is robust since it may include the linear light source in each measurement as a reference. In addition it provides a high directional resolution in the vicinity of the specular direction, typically in the range of 0.1° and higher [6, 7].

### 2.1 Display BRDF

In the mid-1990s, Kelley and his colleagues at the NIST FPD lab analyzed application of the ISO 9241-7 measurement setups to LCD monitors with scattering AG-layers and they concluded, that the complications introduced by the *haze* component of reflectance asked for a new approach to characterization of the reflections of such displays [5]. The radiance/luminance (used synonymously in this paper) reflected by a display in the specular direction is generally the sum of 3 components:

- the ***scattered*** *Lambertian diffuse* and *haze* component, the luminance level of both being determined by the *illuminance*, and,
- the luminance of the ***non-scattered*** *mirror-like* reflection which is given by the *luminance* of the light source in the specular direction.

These 3 components are not mutually independent, the incident radiant/luminous flux is distributed among them depending on details of the sample properties and structure and on the measurement arrangement. Once these basic reflection components are determined and specified, the luminance reflected in a range of directions of observation not too far from the display normal can be calculated for arbitrary arrangements and dimensions of light sources in the surroundings of the display.

Inspired by the visual analysis of reflectance patterns under *point source illumination* [5] and by the *variable aperture source (VAS) method* introduced by Kubota in 1992 [8], the new approach is based on electronic luminance or tristimulus images recorded with an imaging LMD (photometer or colorimeter), followed by analysis of the lateral distribution of luminance or XYZ to obtain the directional distribution of scattered light [6, 7].

The basic idea of PSF analysis is justified by the shift invariance of scattering in direction cosine space as described extensively and in detail by Harvey [9]. For each location on the display under test, DUT, we calculate the direction of light incidence and the direction of the beam entering the LMD aperture to obtain the angle between the local specular direction and the received beam, $\theta^*$ and the new azimuth angle, $\phi^*$. The recorded luminance levels are thus mapped into a coordinate system which is centered about the specular beam at the zero position on the display under test as shown in Fig. 1.

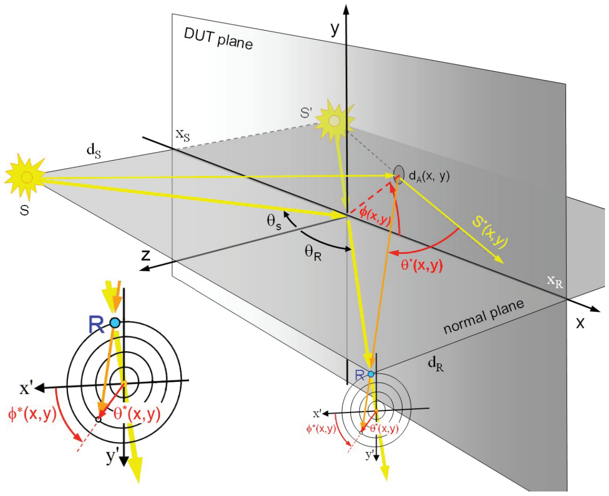


**Figure 1:** A planar DUT illuminated by isotropic point light sources (transmissive, reflective) with the polar coordinate system, $\theta^*$, $\phi^*$, centered on the specular beam at x = y = 0.

## 3 Identification of reflectance components

Due to the instrumental efforts usually required for acquisition of BRDF data, first attempts to identify the 3 components of reflection were based on analysis of the curves specifying reflected luminance as a function of the aperture of a uniform light source in the specular direction (*VAS characteristic*) [10]. The VAS approach has recently been extended by Hertel et al. [11] based on an extrapolation technique, by Becker [12] via numerical fitting of high-resolution BRDF data obtained from PSF analysis and by Penczek [13] via implementation of the concept of a ring shaped illumination first mentioned in 1998 [5].

Separation of the reflection components is achieved as follows:

1 In a first step, the Lambertian component is measured "far away" from the angle of light incidence (e.g. ≥ 45°), based on the assumption that at such angular distances the haze components have dropped to sufficiently small values. The Lambertian component is subtracted from the total reflected luminance.

2 Then, the *haze* component of the corrected curves is numerically fitted to suitable peak functions (e.g. Lorentzian, dashed curves in Fig. 2) and subtracted to yield the unscattered *mirror component*.

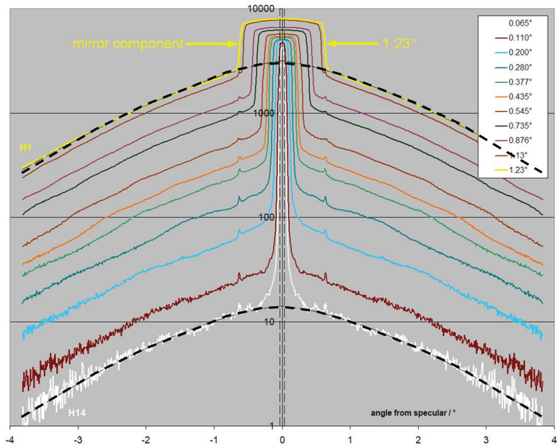


**Figure 2:** Reflected luminance as a function of the angle to specular, $\theta^*$, for a range of aperture sizes of the light source (i.e. levels of illuminance).

While Fig. 2 illustrates the variation of BRDF profiles for 11 light source aperture dimensions, with a distinctly visible mirror component on top of the haze, we are now targeting to reduce that number to just 2 or 3. This reduction is based on determination of the *VAS characteristic* as shown in Fig. 3 by integration of the BRDF profile obtained with the smallest source aperture and its relation to the three components of reflection [12].

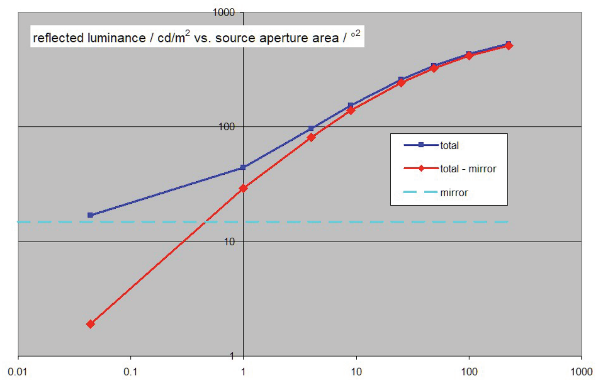


**Figure 3:** Reflected luminance of an LCD screen with AG coating vs. source aperture area, total luminance and haze only (red curve).

Two reference samples are generally included in the measurements for PSF analysis:

1 a *calibrated reflecting diffuser* for monitoring of the illuminance level at the field of measurement, and
2 a *calibrated non-scattering mirror* (e.g. polished black glass) for evaluation of the source aperture diameter and for determination of the variation of the luminance level across that aperture.

The luminance of the *scattered components haze* and *Lambertian* can be specified in terms of a *reflectance factor* (i.e. related to a calibrated reflecting diffuser) and the mirror component can be specified as a fraction of the luminance of the light source determined e.g. via a calibrated mirror. The *reflectance factor* (CIE ILV 17-24-070) of the mirror component as a function of illuminance however is - counterintuitively - decreasing hyperbolically with illuminance.

## 4 Reflectance from light sources with arbitrary dimensions

Each illumination condition in the surround of a display under test can be constructed from arrays of elementary light sources specified by their size, shape, position and luminance. Accordingly, the luminance reflected in the direction of the observer can be calculated as a superposition of components given by a set of BRDFs and an array of elementary light sources [14].

### 4.1 One single direction of observation

In order to make things easier ISO-9241 has been approximating critical illumination conditions by considering light sources in the specular direction at 15°angle of inclination with 1° and 15° apertures, respectively. Due to the fact that the BRDF of electronic displays does not vary substantially for angles of incidence between normal and 20°, the reflected luminance for close to normal observation directions can be calculated easily as a function of the light source aperture dimension by numerical integration of the BRDF (VAS characteristic, see [12, 14].

Increased efforts are required concerning the BRDF measurements and the numerical calculations when light incidence angles become larger (>30°) and the distribution of light sources more complex.

### 4.2 Variations with direction of observation

The directional distribution of reflected light for sources with extended apertures can be determined by convolution of the BRDF with the illuminator aperture in two dimensions as introduced by Ramamoorthi [15].

## 5 International standardization activities

Measurement and specification of display reflectance has been important during the past decades for the rating of the visual performance of electronic displays (e.g. PC and computer monitors), initially at the workplace only (ISO 9241-7, 13406-2), then also with consideration of a wider range of application cases (e.g. ISO 9241-30x), and, for specification of the performance features of reflective LCDs (e.g. contrast, color gamut) as partly addressed in IEC 61747 Part 6-2: "*Measuring methods for liquid crystal display modules - Reflective type*".

Early requirements for specification of the variation of luminance contrast of reflective LCDs with viewing direction led to the development of a special illumination device (*dome illuminator*) that have been integrated and successfully used in a range of commercial instruments.

Activities in both IEC and ISO initially tried to keep the instrumental efforts for the measurement arrangements and methods low in order to enable widespread adaption and acceptance. These simplifications however also entailed makeshifts for specific display technologies (e.g. cathode ray tube, CRT) with a special combination of reflection components (CRT: Lambertian and mirror-like) which failed as soon as the new component *haze* was introduced by scattering anti-glare layers applied to LCD monitors.

Acceptance of the 3-component display reflectance model [5] in optical laboratories around the globe requires measurement methods that are robust and still affordable and manageable. They must allow for identification of each of the three reflection components in the case of emissive, transmissive and reflective displays, and for separation of the disturbing reflection components (*noise*) from those that forward the intended visual information. Corresponding concepts have been presented recently by Hertel et al. [11], Becker [12] and Penczek et al. [13, 16].

More work remains to be done in the field of ergonomics of hand-held electronic displays where instinctive human control of the observation conditions should be taken into account.

For a more detailed description of the related international standardization activities, their origins, motivations, evolutions and future objectives refer to [17].

## 6 Discussion

During determination of the BSDF from the PSF the following aspects should be taken into consideration:

- In the case of small illuminant apertures (i.e. 0.1° and below) the MTF of the LMD optical system may be a limiting factor (i.e. effecting a reduction of the amplitude of the mirror component);
- in the case of extended source apertures the stray light within the LMD optical system may negatively affect the results and should be considered;
- accurate numerical fitting of the haze function may include more than one single model function;
- the amplitude of the mirror component is sensitive to the approach used for its determination.

The optical system of the LMD is characterized by its own PSF and the corresponding low-pass MTF and stray light which is determined by level and distribution of incoming flux. More work is required for characterization and compensation of these effects.

Evaluation of the BSDF from the PSF is based on the following requirements:

1. the optical properties of the DUT must be uniform across the region included in the measurement; this condition however must be fulfilled in the case of visual displays anyway;
2. the angle of inclination of incident light must be small enough to keep variations of the Fresnel reflection coefficients small within the DUT region included in the measurement (e.g. $\theta_i \leq 20°$).

The limitation to angles of light incidence and observation close to the DUT surface normal represents the most important observer arrangement and the limitation to inclination angles close to the specular direction (e.g. up to 20°) still captures those components of reflection that are most important for the visual experience of the observer.

With the extension to large angles of light incidence and application of the imaging LMD as a spot meter in these cases, the PSF-to-BSDF method could be the method of choice for affordable visual display related BSDF measurements.

## 7 Conclusion

Despite some limitations, PSF analysis offers several features that support ease and robustness in the case of display reflection measurements:

- directional variations can be measured quickly and with high resolution in the vicinity of the specular direction without motorized scanning,
- with the extension to large angles of light incidence (imaging LMD → spot LMD), the PSF-to-BSDF method could be the method of choice for affordable full range BSDF measurements;
- adjustment and alignment of the setup are controllable by real-time images provided by the LMD,
- the peak intensity reference of reflected or transmitted light in the regular direction is never missed;
- inclusion of two reference standards (calibrated reflecting diffuser and non-scattering mirror) increases the verifiability of the method, and
- colorimetric analysis is possible with imaging colorimeters or with tunable light sources.

- The BSDF from PSF method is suited for qualitative analysis of the directional distribution of scattered and diffracted light as required for identification of the 3 components of reflection;
- quantitative analysis and characterization of BSDF components has been confirmed for the case of identical hardware, comprising illuminator, imaging LMD, their arrangement and alignment;
- quantitative analysis of BSDF components with different hardware requires more work concerning characterization of the imaging LMD with respect to the MTF and to the effect of stray light and the respective compensations and corrections.

The method of obtaining the BSDF from the PSF thus provides a range of metrological benefits at a minimum of instrumental efforts. It offers access to identification and separation of disturbing reflections (*visual noise*) from those that forward visual information (*visual signal*) as a basis for optimization of the visual and ergonomic performance of electronic display system.

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