New approach for directional analysis of scattered light

This application note describes how the bidirectional scattering distribution function (BSDF) of arbitrary light scattering surfaces can be determined from the point spread function (PSF) with the help of a simple measurement setup, employing the LumiCam imaging photometers and colorimeters from Instrument Systems and a point light source. The presented method allows for a fast and cost-effective identification and separation of specular and non-specular components and thus evaluation of appearance characteristics like, e.g., haze or distinctness of image. Typical applications are shown for both, measurement in reflection (determining the BRDF) and in transmission (determining the BTDF).
1. INTRODUCTION

The bidirectional scattering distribution function (BSDF) mathematically describes the reflection and transmission of light of a specific material. In other words, the BSDF describes the visual appearance of a material. Typical appearance characteristics according to the ASTM E284 standard [1] terminology of appearance are, e.g., haze, gloss, distinctness of image, clarity, reflectance factor and sheen. The analysis of these characteristics are important for a wide range of materials like flat panel displays and their optical components (anti-glare layers, touch panels, diffusers etc), paintwork or – more generally – any surfaces or films whose appearance is of relevance.

Commonly, the determination of the BSDF is either very time-consuming because mechanical scanning is required, or expensive, if for example a conoscope is used. Here we present a new approach utilizing a simple measurement setup that enables a fast and cost-effective determination of the BSDF.

2. BACKGROUND AND MOTIVATION

The BSDF provides a general and complete description of the reflective and transmissive properties of surfaces/materials. It is a function of the direction of light incidence (index i), the direction of observation (index r), the wavelength of light (λ) and its state of polarization (p).

\[ d L_r (\theta_r, \phi_r) = B (\theta_i, \phi_i, \theta_r, \phi_r, \lambda, p) dE_i (\theta_i, \phi_i) \]

$L_r$, $B$, and $E_i$ thereby represent the reflected / transmitted luminance, the bidirectional scattering distribution function and the incident light (i.e. the illuminance of the incident light), respectively.

The BSDF can be separated into two parts, the BRDF describing the reflection of incident light (bidirectional reflectance distribution function) and the BTDF (bidirectional transmittance distribution function) describing transmitted light.

**BRDF**

Reflections of ambient light sources in electronic display screens are disturbing and annoying in several ways:

- They reduce both contrast and color saturation of the visual information to be presented to the observer,
- Reflected images of light sources are causing focusing conflicts, i.e. the eye of the observer is undecided whether to focus on the distant light source or on the nearby display screen. Such a conflict may distract the attention of the observer and cause unpleasant sensations (e.g. dizziness),
- The reflected luminance of small or large area light sources result in glare, thus causing one more visually disturbing effect for the observer.

In order to optimize display screens to make them suitable for extended working periods under a wide range of ambient illumination conditions, reflections from the display should be controlled to a degree that is depending on the nature of the application and its duration.

Scattering micro-structures are effectively used for control of reflections since the early days of liquid crystal displays (anti-glare layers). These micro-structures may either be applied directly to the surface of the top polarizer film (by e.g. embossing) or the display system, in many cases in combination with a touch sensitive input device, may be covered by a glass substrate with a scattering micro-structured surface.

For qualification of electronic devices with display screens for specific applications (e.g. for use in airplane cockpits, or for automotive applications) the reflectance of the display must be measured and characterized as a basis for purchasing decisions. Similar evaluations are required for systematic optimization of display systems by manufacturers with respect to reflections, sparkle, distinctness of image, etc.
Depending on the focus of interest, the measured quantity can be the reflected luminance or the reflected radiance from which additional colorimetric characteristics of scattered light can be obtained.

**BTDF**

For an even, uniform distribution of light emitted by point or line sources, diffusing materials are required. Applications include backlight units (BLU) for LCD monitors and screens, where the light from fluorescent tubes (line sources) or more recently, from LEDs (point sources) is to be evenly distributed over areas up to 1.2 m\(^2\) (in the case of TV-screens with 65" diagonal) without modification of the spectrum of emission. Similar tasks exist in the indoor lighting industry, where light from point and line sources has to be evenly distributed over the area of lighting panels.

During the development of optimized polymer materials that can be used for uniform distribution of light without affecting the emission spectrum (shift of chromaticity) and with a good efficiency (i.e. without wasting radiant flux by absorption) fast, reliable and robust measurement methods are required in the laboratory.

**New approach to determine the BSDF**

In principle, there are two different approaches to determine the BSDF. One is to use a system that mechanically scans a range of observation directions to analyze the angular dependence. This can be realized by bulky high-precision measurement systems as goniophotometers or goniospectroradiometers. Another approach are conoscopic measurements. Those lens systems are commonly quite expensive (high-end conoscopic systems) or limited to transmissive measurements (add-on conoscopic lenses).

In this note we present a fast and convenient way of measuring the reflectance distribution of planar samples under point source illumination. In comparison to heavy, bulky and costly mechanisms for motorized directional scanning or to approaches using complex and expensive lens systems, the so-called BSDF analysis kit offers a range of advantages that make product and material development more efficient:

- Compact and easy to use setup without moving parts,
- Fast acquisition of raw data and easy evaluation,
- Analysis with respect to directional variations of luminance and chromaticity,
- Evaluation in terms of several appearance related terms (e.g. haze, distinctness of image, etc.).

This application note introduces measurement setup and procedure as well as a range of typical evaluations for both, the BRDF and the BTDF.

### 3. BASIC WORKING PRINCIPLE

Figure 1 explains the basic principle by means of the transmissive configuration of the measurement setup. The plane sample (DUT) is illuminated by the isotropic point light source, \(S\), resulting in an illuminance \(E(x, y)\) that varies across the sample surface. For each area element \(dA(x, y)\) at location \(P(x, y)\) on the DUT surface there is one direction of light incidence, \(\theta_i, \phi_i\), and one direction of scattered light that is received by the imaging light measuring device (ILMD), \(\theta_r, \phi_r\). With the details of the geometry of the setup known, these directions can readily be calculated.
The reflection distribution function, RDF, is given in terms of the difference angle, $\theta^*$, with respect to the specular direction and the azimuth $\phi^*$ (cf. Fig. 2).

**NOTE:** It must be assured that the DUT properties are uniform across the area included in the measurement.

### 4. MEASUREMENT SETUP

The measurement setup comprises the following components (see Fig. 3):

- A LumiCam imaging photometer and colorimeter (for measurement examples presented here, the 6 color filter LumiCam 1300 Advanced was employed in the high dynamic range mode.),
- An isotropic point light source (PLS) with stabilized power supply,
- An optical bench with a sample fixture.

The variation of illuminance (irradiance) across the DUT surface is recorded with a diffuse reflectance standard, e.g. a plate of sintered PFTE powder for correction in the reflectance evaluation process.

The LumiCam 1300 Advanced is focused on the PLS, light source emission must be adjusted to avoid overflow of the imaging photometer and colorimeter and too short exposure time periods. This can be achieved via control of the driving current or with neutral density filters mounted in front of the light source or camera.

**Fig. 2:** Coordinate system centered about the regular direction with spherical coordinates $\theta^*$, $\phi^*$ (left) and their representation in a polar coordinate system (right). Intensities are shown as pseudo colors.

**NOTE:** BSDF measurements

**Fig. 3:** Sketch of optical bench with LumiCam 1300 Advanced, PLS and DUT. The distances of LumiCam and PLS with respect to the DUT determine the angular range of measurements and the resolution.


5. MEASUREMENT PROCEDURE

General (any setup)

1. Switch the light source on and allow the emission to stabilize. This can be checked via the voltage drop across the LED light source.

2. Focus the LumiCam 1300/2400 on the light source and measure the emission of the source (luminance and chromaticity) as reference for the evaluations either in the unfolded setup, or via a calibrated specular mirror.

3. Determine the image distance with an object of known dimensions (e.g. a ruled reticle) in the plane of the PLS.

Measurement in reflection (BRDF)

4. Measure the illuminance (irradiance) across the plane of the sample, \( E(x, y) \) with a calibrated Lambertian diffuse reflector. Alternatively, and for convenience of operation, this variation can be calculated from the geometry of the setup (recommended).

5. Fix the device under test in the setup, choose the angle of light incidence and the distances of both LumiCam and PLS with respect to the center of the DUT. The angle of the LuminCam, \( \theta_r \), is chosen identical to the angle \( \theta_i \) to place the specular reflection peak into the center of the luminance/chromaticity image.

6. Measure the lateral distribution of reflected luminance/chromaticity of the sample and store the result data for subsequent evaluation. Alternatively, and for convenience of operation, this distribution can be calculated from the geometry of the setup.

Measurement in transmission (BTDF)

4. Measure the illuminance (irradiance) across the plane of the sample, \( E(x, y) \) either with a transmissive diffuser or with a Lambertian diffuse reflector in the folded arrangement. In the latter case the light source shall be normal to the reflector plane and the LumiCam inclination shall be as small as possible. Alternatively, and for convenience of operation, this variation can be calculated from the geometry of the setup (recommended).

5. Fix the device under test in the setup, choose the distances of both LumiCam and PLS with respect to the center of the DUT.

6. Measure the lateral distribution of reflected luminance and chromaticity of the sample and store the result data for subsequent evaluation.

General (any setup)

7. Perform the geometric transformation to obtain the reflected/transmitted intensities (photometric/colorimetric) as a function of the spherical angles \( \theta^* \) and \( \phi^* \). This can be done with the corresponding software “BSDFMeter”\(^1\).

8. The data \( r_{i\rightarrow s}(\theta^*, \phi^*) \) is available for graphical representation and for further evaluation.

\(^1\) This software is part of the BSDF toolkit offered by Instrument Systems.
6. APPLICATION EXAMPLE #1: BRDF OF DIFFERENTLY COATED DISPLAYS

The BRDF of displays typically consists of mirror-like specular and scattered (Haze and Lambertian) components. Displays (or any other materials) with predominantly specular reflections produce virtual images in the direction of the specular component [5]. The diffuse components arise from light scattered out of the specular direction, with the Lambertian components being independent of the angle of inclination and the Haze component being centered around the specular reflection. This is illustrated in Figure 4 below, showing the reflected light (by means of luminance in arbitrary units) of a display with strong specular reflection, i.e. without anti-glare (AG) layer.

**Fig. 4:** (a) 3D illustration of the typical (main) components of reflection based on a BRDF measurement on a flat panel display without anti-glare treatment. (b) Description of different BRDF components taken from the “Information Display Measurements Standard (IDMS)” [5].

### Illustrative evaluations

In order to illustrate the capabilities of the measurement method we have evaluated the reflectance characteristics of four state-of-the-art computer display screens, one from a tablet computer without AG-layer, two displays from notebook computers with different AG-treatments, and a desktop computer monitor with a strongly scattering AG-polarizer.

The reflectance distribution of the non-scattering display of the tablet computer (yellow curve in Fig. 6) basically is the same as that of a mirror, it features a sharp peak with a steep drop-off with increasing angle of inclination. The modulations that are obvious at the edges of the curve are caused by diffraction of the sub-pixel matrix of the display (FFS LCD).

The moderately scattering AG layer of the first notebook computer display (blue line in Fig. 6) causes a considerable reduction of luminance reflected in the specular direction and reduces the transfer of distinct images of light sources.
A further increase of scattering also decreases the amount of light reflected in the specular direction (cyan and red lines). The reflectance can be characterized by the specular reflectance factor, $R_s$, given as:

$$DUT R_s [%]$$

<table>
<thead>
<tr>
<th>DUT</th>
<th>$R_s [%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>no AG</td>
<td>8.687%</td>
</tr>
<tr>
<td>moderate AG</td>
<td>0.302%</td>
</tr>
<tr>
<td>increasing AG</td>
<td>0.021%</td>
</tr>
<tr>
<td>strong AG</td>
<td>0.008%</td>
</tr>
</tbody>
</table>

The curves distinctly illustrate the fact that increasing scattering, visible by an increasing width of the curve, decreases the amount of light reflected in the specular direction and thus reduces the amount of disturbing reflections.

Characteristic values can be obtained from the reflectance distribution functions in terms of a generalized Haze level similar to the definitions of ASTM E430 - 11 [2] as follows:

$$Haze [%] = \frac{\sum_{\text{window} - 1} L(\theta^*) + \sum_{\text{window} + 1} L(\theta^*)}{2 \cdot \sum_{\text{window} - \text{specular}} L(\theta^*)}$$

with windows over which the reflected luminance is integrated, located at the specular direction and symmetrically off-specular. The width of the specular window should be chosen according to the width of the system signature (width of reflectance peak without scattering) and the off-specular windows are usually $2^\circ$ or $5^\circ$ from the specular direction.

Table 1: Reflectance factor in the specular (i.e. mirror) direction, $R_s$, for the four sample displays.
The Haze values according to this procedure resulting for the four measured samples are:

<table>
<thead>
<tr>
<th>DUT</th>
<th>Haze [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>no AG</td>
<td>0%</td>
</tr>
<tr>
<td>moderate AG</td>
<td>2%</td>
</tr>
<tr>
<td>increasing AG</td>
<td>19%</td>
</tr>
<tr>
<td>strong AG</td>
<td>60%</td>
</tr>
</tbody>
</table>

Table 2: Haze values of the different samples calculated from the profiles shown in Fig. 7 according to eq. (1).

7. APPLICATION EXAMPLE #2: BTDF

Just like the BRDF, the BTDF of a material can have scattered and non-scattered components. A characterization in the transmissive measurement setup is suitable for all transparent or semi-transparent materials as for example optical components of a display (without the module). 12 different samples were analyzed with respect to directional distribution, Haze, and colorimetric variation.

Illustrative evaluations

Figures 8 and 9 below show typical directional images in pseudo-color representation resulting from the PSF Analysis.

Fig. 8: Pseudo color representation with logarithmic scaling of the directional transmittance distribution of one sample with the polar coordinate system for specification of the difference angle \( \theta^* \) and the azimuth \( \phi^* \). The concentric circles correspond to steps of \( \Delta \theta^* = 5^\circ \). The intensity distribution recorded by the LumiCam clearly shows the edges of the sample as well as the label attached for identification of the sample.

Fig. 9: Pseudo color representation with logarithmic scaling of the directional transmittance distribution of four samples.

A luminance profile was evaluated for each of the twelve samples in the horizontal direction (i.e. \( \phi^* = 0^\circ, 180^\circ \)) from \( \theta^* = -20^\circ \) to \( \theta^* = 20^\circ \). These intensity (luminance) profiles are plotted together for easy comparison of the scattering properties of the samples. Figure 10 shows the profiles for the samples 1-4 plus light source profile (yellow). In the case of an isotropic material, the same transmitted luminance is expected for all azimuth angles.

Fig. 10: Transmissive scattering characteristics of four out of twelve samples (normalized, log. scaling) shown together with the light source as a reference (yellow curve) and for easy identification of specular components.
A readily available characteristic value is the drop of transmittance in the regular direction caused by scattering (see, e.g., ASTM D1746 - 15 [3] and [6]).

A variety of further characteristic values can be derived from the scattering distribution curves, e.g. the full (angular) width at half maximum, the Haze at 2° or 5° off-specular, etc. according to the requirements of the specific task to be solved. Since the scattering distribution functions are available numerically, suitable characteristic values can easily be calculated.

Colorimetric evaluation

From the data recorded by the LumiCam the chromaticity in terms of $u'$ and $v'$ can be evaluated. Figure 9 below shows such an analysis for sample #3 for nine angles of inclination in the horizontal plane between -20° and +20° (5° steps).

In the resulting traces in the CIE 1976 chromaticity diagram the color coordinates should be the same for $+\theta^*$ and $-\theta^*$ as shown in Fig. 11 above. Deviations from that identity are caused by non-uniformities of the samples over the regions included in the measurements.

The location of the chromaticity for $\theta^* = 0$ and the chromaticity of the light source are shown for reference.

Directional distribution of scattered light

From the directional distribution one can also analyze the regular transmittance and Haze values of the 12 different samples.

Interestingly, the 12 samples investigated can be grouped into sets of four samples. As shown in Figs. 12 and 13, within group one and two (samples 1-4 and 5-8) the regular transmission of the decreases with increasing number and, correspondingly, the Haze value increases. This is not true, however, for samples 9-12.
8. VALIDATION

The new method for BSDF analysis presented here was validated by comparison with different established measurement devices. Details can be found in [4]. Quite general it has to be considered that quantitative comparisons of different BSDF measurement setups are difficult because results always depend on the setup’s system signature, i.e. on the light source itself, the geometry of the setup and the measurement device etc.

9. LIMITATIONS

The proposed approach to high-resolution BSDF analysis based on the evaluation of the point spread function capture with an LumiCam 1300/2400 is ideal for angles of light inclination below 15°. For larger angles, the effect of the variation of the Fresnel coefficient and that of the shape asymmetry of the reflection distribution function with angle of incidence on the results obtained from the point spread function is no longer negligible [4].

Precondition for this measurement approach is a uniform sample over the area analyzed with an LumiCam Series photometer and colorimeter.

10. CONCLUSION

We present a novel approach to determine the BSDF, based on the evaluation of the point spread function measured with an imaging light measurement device. The proposed method not only employs a simple, cost effective measurement setup without moving parts, it also determines the BSDF in a single measurement and allows for colorimetric analyses. The results, centered around the specular direction provide a very high directional resolution, but are limited in the range of inclinations.

REFERENCES
