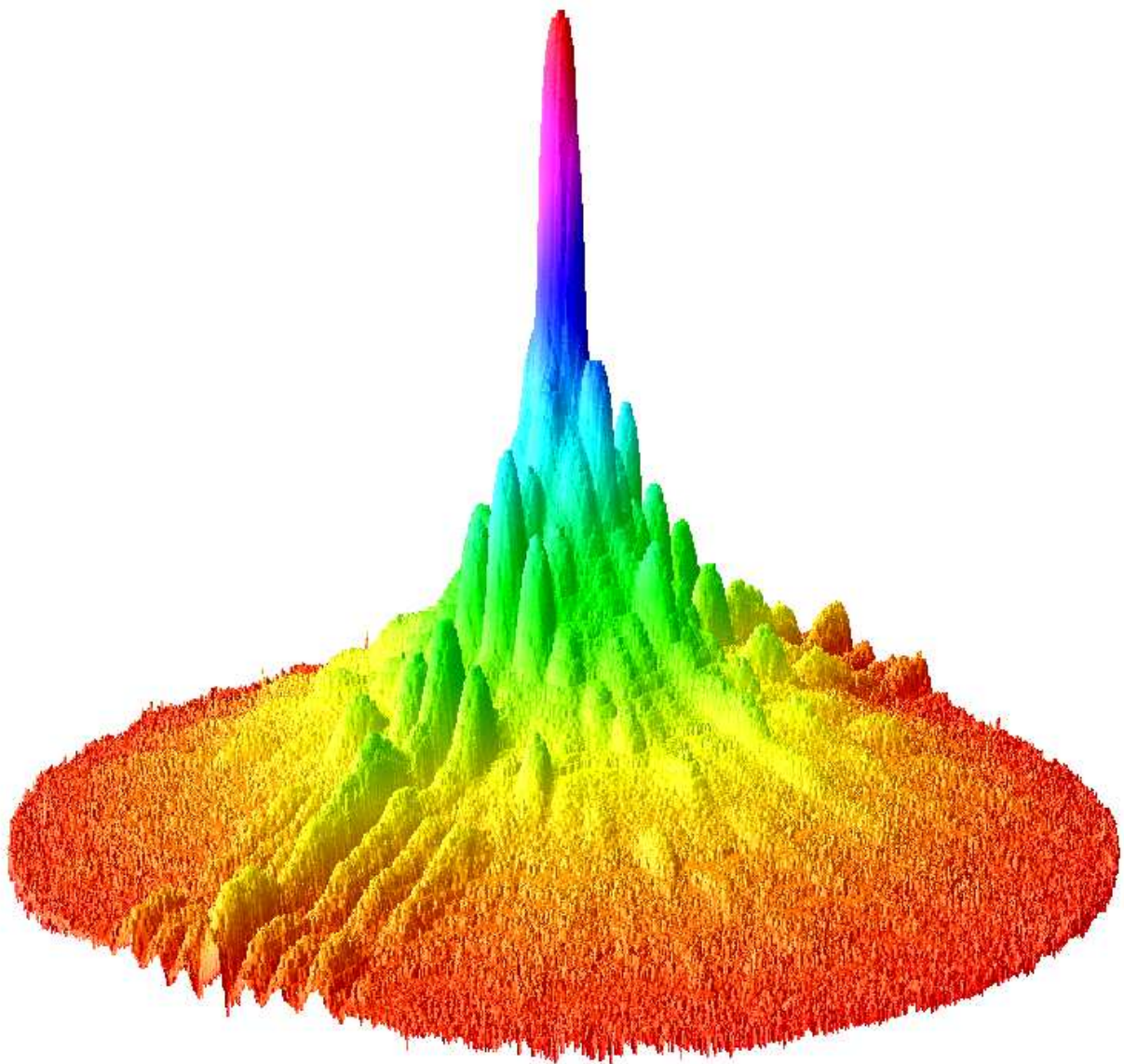


BSDF-Meter

Fast, high-resolution analysis of light scattering
with imaging photometers and colorimeters





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1 Introduction

The directional distribution of light scattered during transmission and reflection can be evaluated by sequential goniometric scanning, by conoscopic imaging, by projection on a screen and by catadioptric imaging. These approaches are usually based on complex mechanical goniometer setups, or require arrangements with special optical components (e.g. hemispherical screens, spherical or elliptical mirrors, complex lens systems, etc.).

Alternatively, directional scanning can be realized in the case of planar or cylindrical samples illuminated by point light sources or linear lamps, respectively, by analysis of the lateral distribution of the scattered light (point-spread or line-spread function, PSF, LSF, respectively, depending on the light source geometry).

Such approaches have been reported in 1998 for evaluation of the *bidirectional reflectance distribution function* (BRDF) of textile fabric [1] and of paper [2] in cylindrical geometries.

At the same time display metrologists used to visually explore the reflectance of display screens with a point light source in order to distinguish and rate the three main reflection components specular, Lambertian and haze [3] as illustrated in Figs. 1 and 2. Since the lateral distribution of light reflected from samples under point source illumination obviously contains all information otherwise provided by the BRDF, the question arose, how such lateral intensity distributions could be transformed into the conventional BRDF. A method to accomplish this (BRDF of planar display screens under point-source illumination) had then been published in 2004 [4].

While high-resolution BRDF measurement and evaluation over a wide range of directions provides useful details about the reflectance of electronic display devices, the ergonomic rating of displays only requires the knowledge of a special subset, i.e., the specular reflectance factors for two sizes of source aperture (e.g., 1° and 15° according to ISO 13406-2) and specific angles of incidence for calculation of the reflected luminance (causing glare) under specified illumination conditions (hemispherical diffuse and directional).

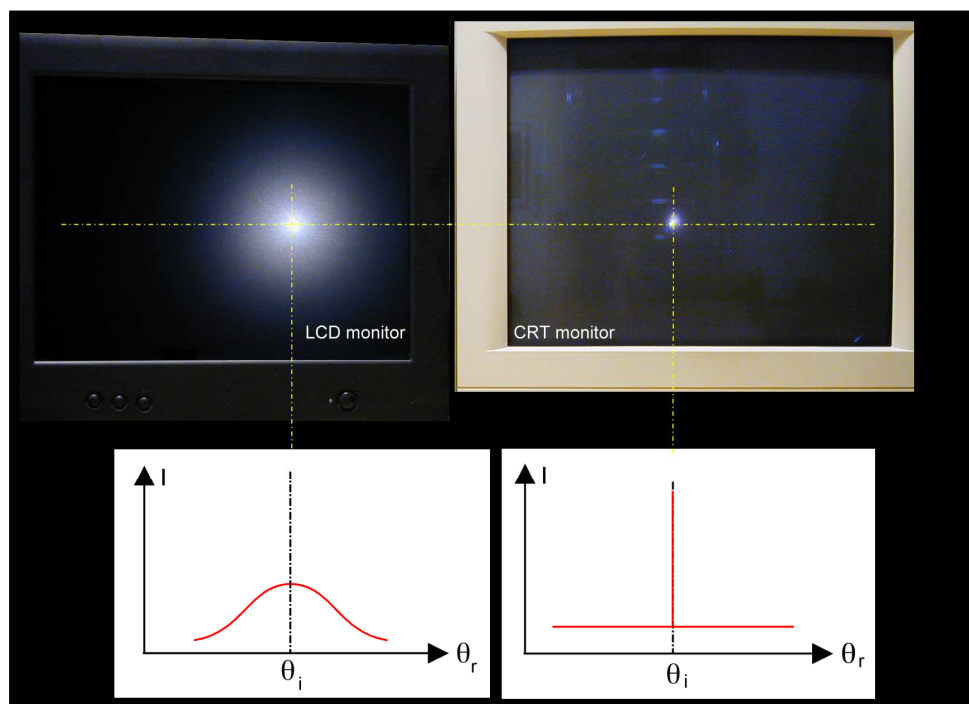


Figure 1: Reflection patterns of two computer monitor screens under point light source illumination. The LCD monitor shows a *haze* component which is fading out with increasing distance from the *specular direction*. The CRT monitor shows the superposition of two components: the *Lambertian* component obvious as a uniform brightening of the display surface and *specular* component which is the mirror image of the light source.



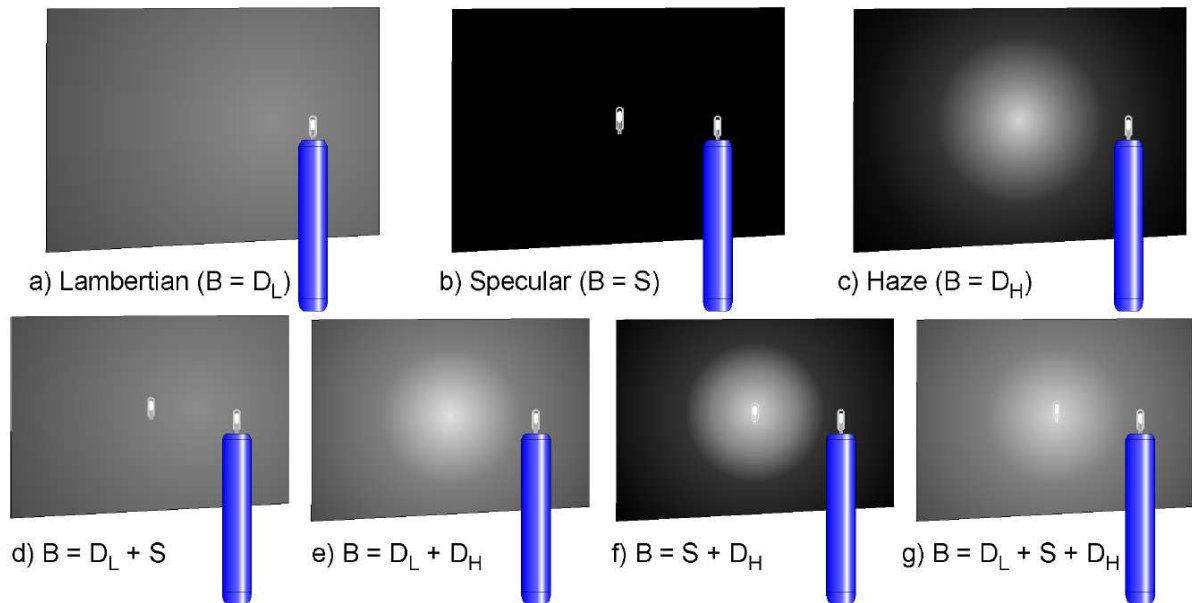


Fig. 2. Illustration of the three types of reflection found in modern electronic displays. B refers to the BRDF that can have a diffuse (Lambertian) component, D_L , a mirror-like specular component that produces a distinct image, S , and a haze component, D_H . One component must exist. There are four combinations of the three components. Any or all of the three components can exist nontrivially, or one component can dominate while the other two components make a trivial contribution to the reflection (as in the case of the first three illustrations).

Figure 2: Vesa Flat Panel Display Measurement Standard (2001), page 272, illustrating point-spread functions of the three basic reflection components (Lambertian, specular and haze) and their combinations.

In order to obtain reflectance data over the required limited range of directions with sufficient accuracy and robustness in combination with the details of high-resolution BRDF data without mechanical scanning, we introduced the following measurement approach ([4], 2004):

- ◆ application of an imaging photometer/colorimeter for recording of the lateral distribution of reflected luminance and chromaticity,
- ◆ a high-intensity isotropic small-area light source (LED), and
- ◆ numerical data processing to obtain the BRDF.

The basic idea of the approach proposed here is to measure the reflected luminance from each area element on the sample at locations $P(x, y)$, and to transform these intensity values adequately to obtain the BRDF characteristics in terms of the angular distance to the direction of the specular beam.

When the point light source (PLS) is located behind a transparent or translucent sample, the directional variation of transmittance can be measured in the same way as the reflectance.

In order to derive a procedure for the transformation between a measured PSF (i.e., *point-spread function*) and the BRDF, we first introduce the geometry of the PSF setup as shown in Fig. 3.

NOTE: It must be assured that the optical properties of the *device under test*, DUT, are uniform across the area included in the measurement.



2 Basic working principle

The planar sample (DUT) is illuminated by a point light source with isotropic emission, S (or S' for the transmissive case), resulting in an illuminance $E(x, y)$ that varies across the sample surface. For each area element $dA(x, y)$ at the location $P(x, y)$ on the DUT surface there is **one specific direction of light incidence**, θ_i, ϕ_i , and **one specific direction of scattered light** that is received by the iLMD aperture, R, θ_r, ϕ_r . With the details of the geometry of the setup known, these directions can readily be calculated. The *reflectance distribution function*, RDF, is given in terms of the difference angle, θ^* , with respect to the specular direction and of the azimuth ϕ^* .

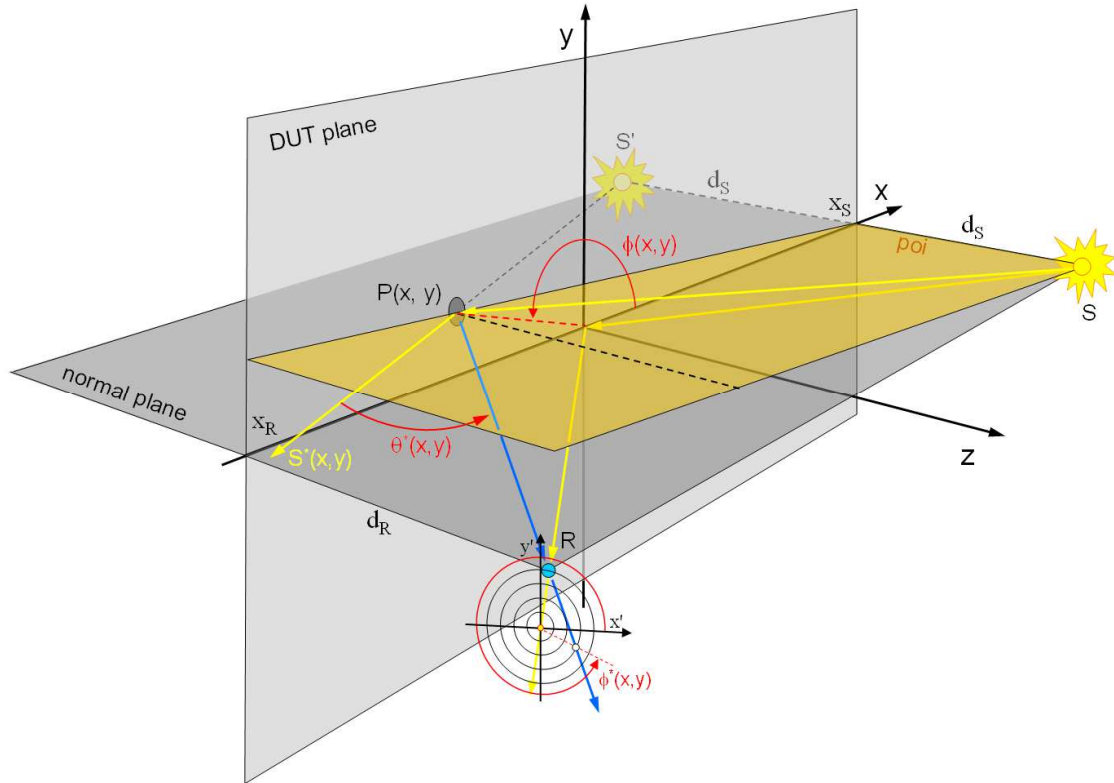


Figure 3: Illustration of the geometry of measurement with a planar device under test (DUT), isotropic point light source (S and S') and imaging light measurement device (receiver, R) for the reflective and the transmissive case (S'). Light source and receiver are located in a plane normal to the planar sample and the area element at location $P(x, y)$ defines the plane of light incidence (poi) with the light source. Only such light rays contribute to the reflected/transmitted intensity that are entering the receiver aperture, R .

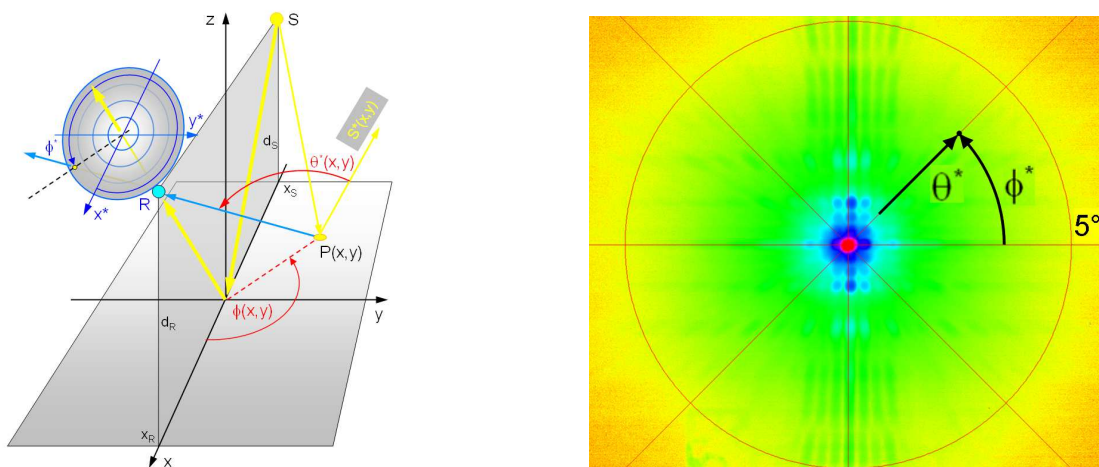


Figure 4: Coordinate system centered about the specular direction with spherical coordinates θ^*, ϕ^* (left) and their representation in a polar coordinate system (right). Intensities are shown as pseudo colors.



2.1 PSF-analysis vs. BRDF measurement

In conventional BRDF/BTDF measurement approaches (realized either with mechanical directional scanning or with conoscopic imaging), one element of the surface of the DUT is directionally illuminated and the light transmitted or reflected at this area element is directionally scanned.

In the case of conoscopic imaging the planar sample is located in the front focal plane of the conoscopic transform lens which produces an image of the directional distribution of the light in the field of measurement in its rear focal plane. This image is called "directions image".

The alternative method applied here illuminates the sample surface with a point light source with isotropic emission and records the reflected/transmitted luminance (chromaticity) across the sample area with an imaging light measurement device (iLMD). With the geometry of the setup according to Fig. 3 known, the direction of light incidence and the direction of reflected and transmitted (received) light can be calculated as a function of the difference angle, θ^* , which is the angular difference between the beam reflected in the specular direction (S^*) and the received beam (blue arrows in Figs. 3 and 4).

While in the conventional BRDF case the direction of light incidence remains constant and the direction of the receiver is scanned (or vice versa), in the PSF analysis both direction of light incidence and reflection vary with the position of the area element under consideration, $P(x, y)$.

In order to evaluate the effect of this simultaneous variation of both directions we have carried out model calculations based on the 1D-geometries (side view) shown in Fig. 6. The table in Fig. 7 reveals that for an angle of light incidence of 5.6° the difference between both approaches does not exceed 0.2° within an angular range of $\pm 15^\circ$. That difference is mainly given by the variation of the Fresnel coefficient which describes the specular reflectance as a function of the angle of light incidence. The Fresnel coefficient for a dielectric surface with an index of refraction of 1.5 (e.g. glass) reaches a variation of 1% with respect to the normal incidence only above 22° light incidence [5].

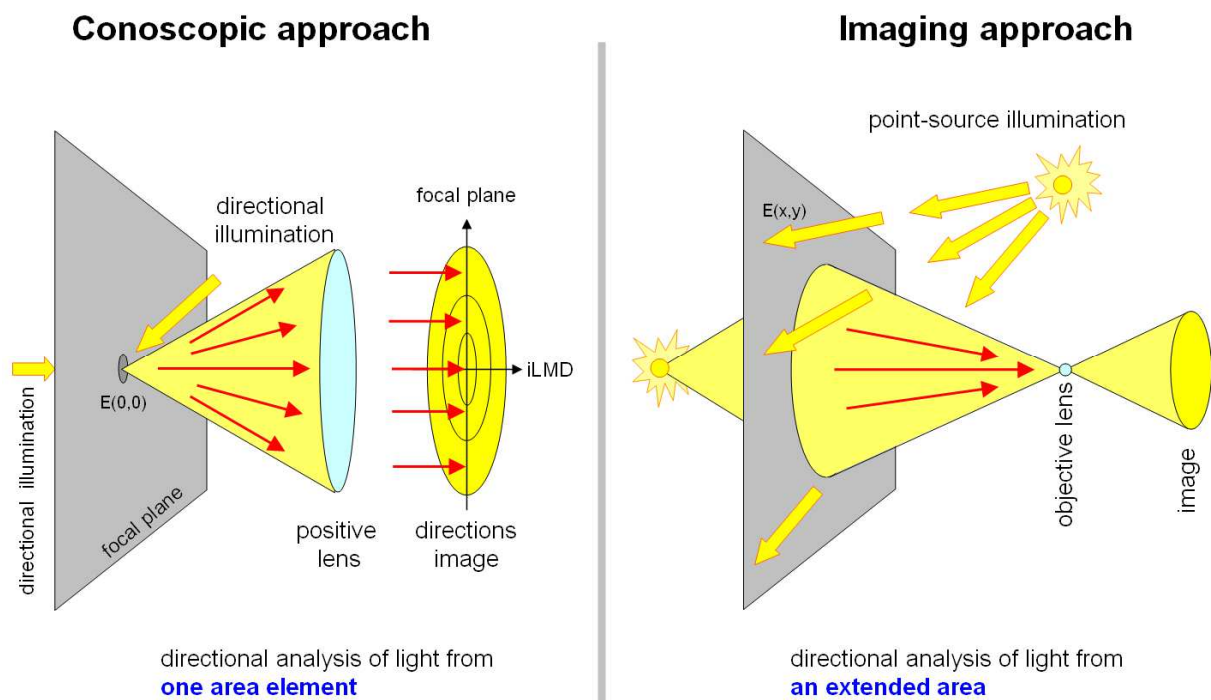
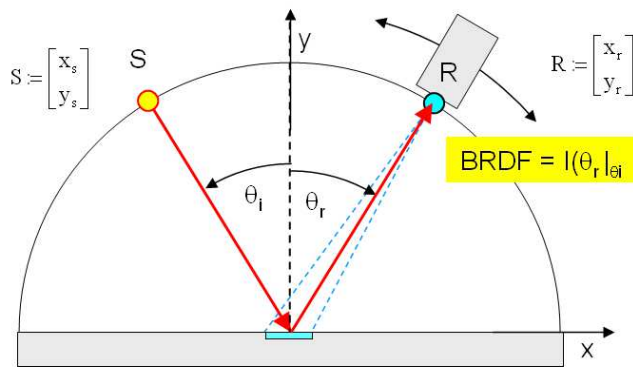
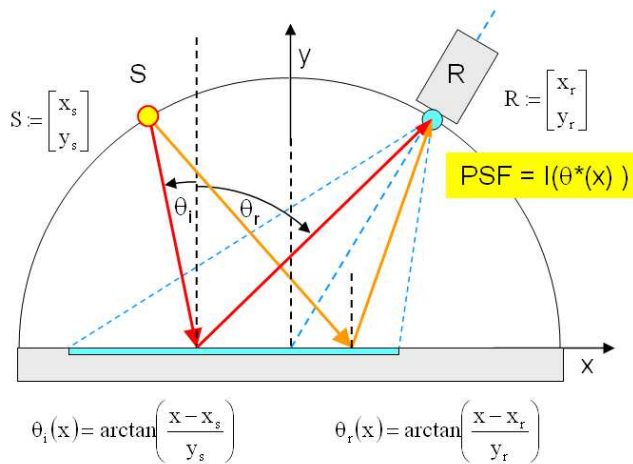


Figure 5: Basic differences between the conoscopic approach vs. PSF-imaging.



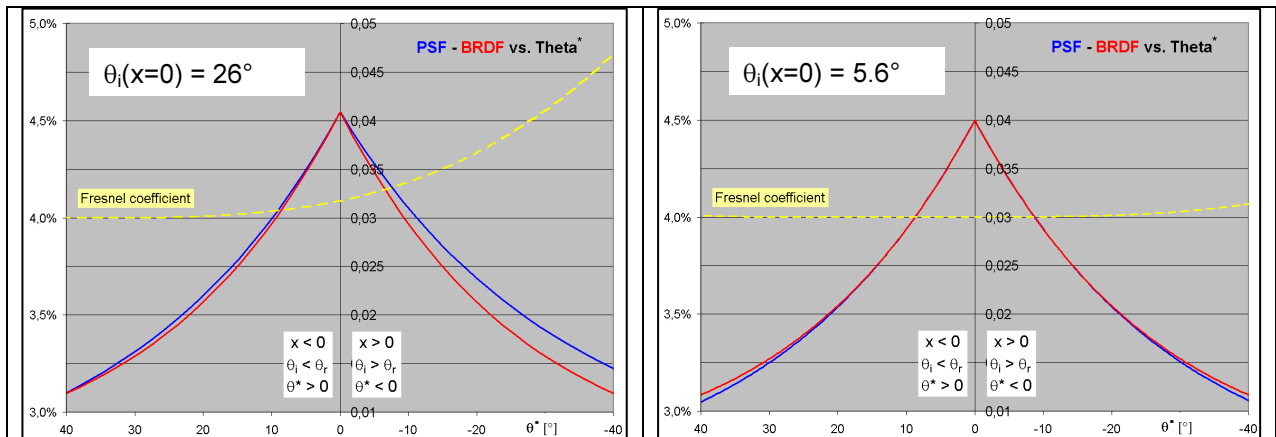


Conventional BRDF setup with the field of measurement on the sample surface (given by the optical system of the receiver, R), illuminated from one direction, θ_i , while the receiver is scanning the range of inclination angles, θ_r , for analysis of the variation of reflectance.



Setup for PSF-analysis. The isotropic light source S illuminates the surface area of the sample that is included in the measurement while the receiver, R (e.g. imaging LMD) records the intensity of reflected light across the sample surface area simultaneously. The angle of inclination of incident light, θ_i and the angle of inclination of received light, θ_r , are both functions of the coordinate x and obtained by the formulas shown in the illustration .

Figure 6: 2D setup used for model calculations to compare the results of the conoscopic approach against those of the PSF-imaging and analysis.



$\theta^* [^\circ]$		40	20	0	-20	-40	
$\Delta [\%]$	$\theta_i(x=0)=26^\circ$	0,38	3,09	0,00	11,53	21,40	
$\theta^* [^\circ]$		15	10	5	0	-5	-10
$\Delta [\%]$	$\theta_i(x=0)=5.6^\circ$	-0,19	0,03	0,06	0,00	0,07	0,08

Figure 7: Difference between the reflectance levels from PSF-analysis and BRDF vs. θ^* for two source orientations: $\theta_i(x=0) = 26^\circ$ and $\theta_i(x=0) = 5.6^\circ$.

In order to keep the differences between conventional BRDF measurements and the PSF-analysis as small as possible, the angle of light incidence across the DUT should not vary more than 22° .



3 Measurement setup

The measurement setup comprises the following main components:

- ♦ an imaging photometer/colorimeter (iLMD), including a range of calibrated neutral density (ND) filters to account for the high dynamic range of the measurements (up to 10^{+6} between light source and diffuse reflectance reference panel).
- ♦ a point light source (PLS) with stabilized power supply (i.e. current source),
- ♦ a diffuse reflectance reference panel,
- ♦ an optical bench with a suitable sample fixture.

The basic arrangement of the components is illustrated in Fig. 8 below.

The variation of illuminance (irradiance) across the DUT surface is recorded with a diffuse reflectance reference panel, e.g. a plate of e.g. sintered PTFE powder for consideration of the lateral variation of illuminance $E(x, y)$ in the reflectance evaluation process.

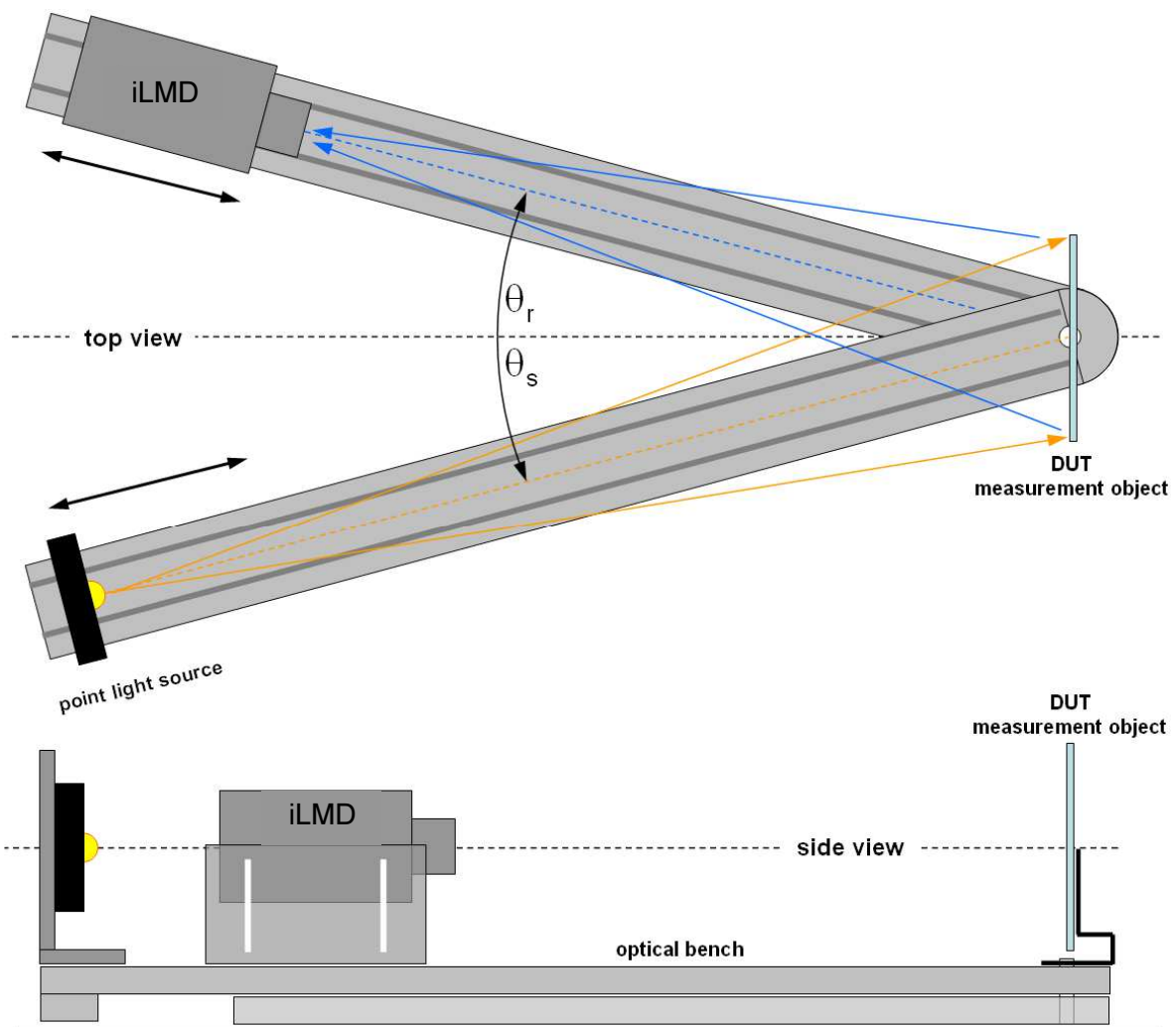


Figure 8: Sketch of optical bench with iLMD, PLS and DUT. The distances of iLMD and PLS with respect to the DUT determine the angular range of measurements and the resolution.

The iLMD must be focused on the light source, light source emission must be adjusted to avoid overflow of the iLMD and too short exposure time periods. This can be achieved via control of the driving current and with neutral density filters mounted in front of the light source.



4 Measurement procedure

- ◆ Fix the device under test in the setup, choose the angle of light incidence and the distances of both iLMD and PLS with respect to the center of the DUT. The angle of the iLMD optical axis, θ_r , is usually chosen identical to the angle θ_i to place the specular reflection peak into the center of the luminance/chromaticity image.
- ◆ Switch the light source on and allow the emission to stabilize. This can be checked via the voltage drop across the LED light source (indicated by the Arroyo source meter).
- ◆ Select imaging conditions (i.e. objective lens, working distance) to completely capture the region of interest (ROI) on the sample surface. Short working distances will result in larger areas and wider ranges of angles of inclination included in the measurement. See Fig. 9.
- ◆ Focus the iLMD on the light source and measure the emission of the source (luminance and chromaticity) as reference for the evaluations, either in the unfolded setup (with otherwise unchanged conditions), or via a calibrated specular mirror (preferably a black glass mirror).
- ◆ Measure a ruled reticle (luminance only) at the location of the light source for determination of the imaging scale of the iLMD as detailed in Fig. 18.
- ◆ Measure the illuminance (irradiance) at the position of the sample, $E(x, y)$ with the diffuse reflectance reference panel.
- ◆ Measure the lateral distribution of transmitted/reflected luminance/chromaticity of the sample.
- ◆ Perform the geometric transformation to obtain the reflectance (photometric/colorimetric) as a function of the spherical angles θ^* and ϕ^* .
- ◆ The data $r_{XYZ}(\theta^*, \phi^*)$ or $t_{XYZ}(\theta^*, \phi^*)$ is available for graphical representation and for further evaluation.

The specular peak of reflectance is usually placed into the center of the detector array of the imaging colorimeter in order to obtain symmetrical directional distributions.

When the specular peak is in the center of the LMD detector array, the angles of light incidence and receiver inclination are identical ($\theta_r = \theta_s$).

The **light source emission** (peak value in specular/regular direction) may be taken into account in two ways:

- 1 in order to establish the **reference luminance** for determination of the reflectance of the sample in the specular direction, R_s . $R_s = Y_{\text{peak}} / Y_{\text{source}}$
- 2 in order to establish the **reference chromaticity** for the light scattered by the sample in comparison to the chromaticity of the light source.



5 BSDF-Meter Software

Software for transformation of lateral luminance/chromaticity variations into directional reflectance/transmittance distribution functions.

Lateral luminance/chromaticity variations as obtained by illumination of a planar sample with an isotropically emitting point light source (i.e. point-spread function, PSF) are recorded with the colorimeter Control Software and each tristimulus component, X, Y and Z, is stored as ASCII data.

The BSDFmeter software only accepts data that has been stored in the format provided by the Colorimeter control software.

5.1 Objects and Data Sets

In the most general case, 3 objects are included in one measurement, each one represented by a data object (data set) in the BSDF-Meter software:

- ◆ **point light-source** (isotropically emitting white or monochromatic light),
- ◆ **diffuse reflectance reference** panel, calibrated in terms of diffuse reflectance,
- ◆ **sample - DUT** to be measured (transmissive and/or reflective).

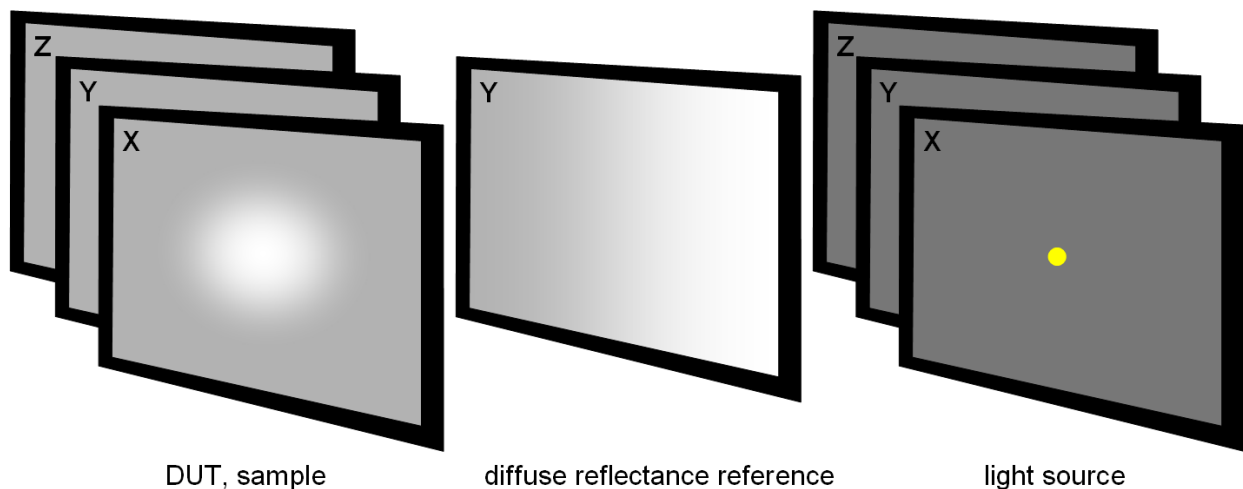


Figure 9: Typical tristimulus records (images) for the sample, the diffuse reflectance reference and for the light source.

The isotropically emitting point-light source provides illuminance for scattering samples and the reference luminance for non-scattering samples. From the PSF of the light source, the system signature can be obtained (i.e. highest directional resolution), the **source luminance** is taken as reference for determination of the reflectance in the mirror direction, R_s , and the **source chromaticity** is taken as reference for determination of color shift induced by scattering. Usually, short wavelengths are scattered more strongly, so the light reflected in the specular direction undergoes a shift into the red part of the spectrum. This red-shift is often distinctly visible in transmissive scattering samples.

Luminance of light source →	reference for reflectance/transmittance in the specular/regular direction
Chromaticity of light source →	reference for variations of chromaticity in the specular/regular direction induced by scattering



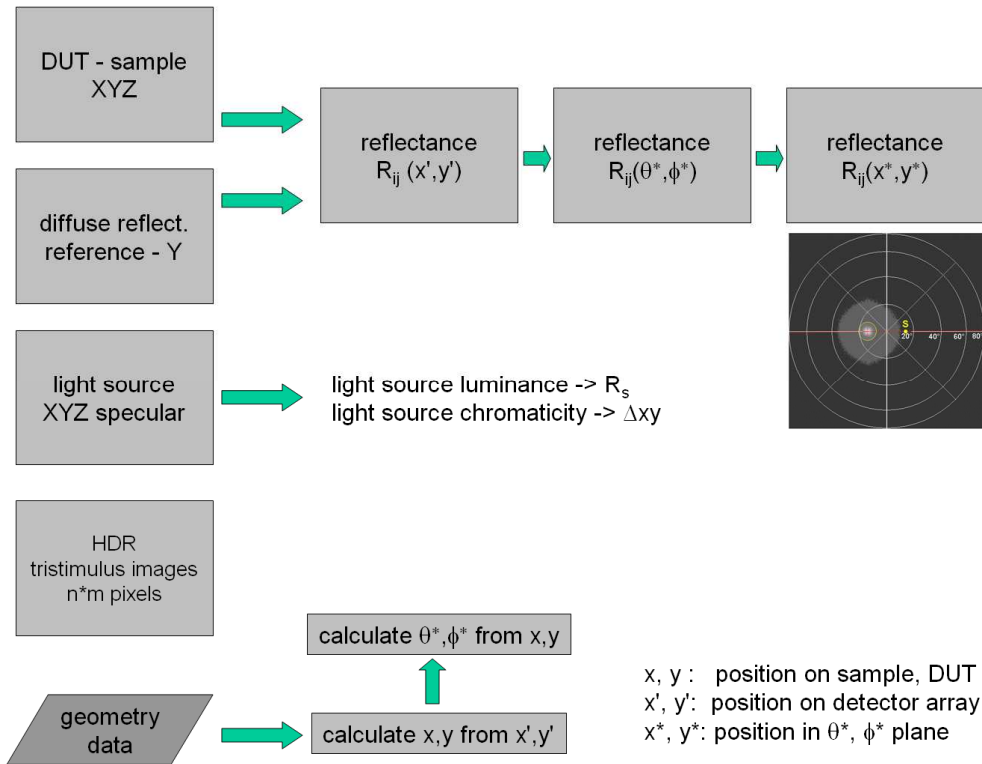


Figure 10: Input data sets and data flow.

The luminance reflected by the **diffuse reflectance reference** panel, L_r , across the surface of the sample, is proportional to the illuminance, and a function of the position on the sample surface, $E(x, y)$.

$$L_r = L_s \cdot \frac{r_s^2}{d(x, y)^2} \cdot \rho_{ref}$$

with	L_s	source luminance
	L_r	reflected luminance
	r_s	radius of light source [m]
	d	distance source to reflectance reference [m]
	ρ_{ref}	reflectance of diffuse reference panel

The reflected luminance is given by the quotient of the light source area (some $\text{mm}^2 = \text{some } 10^{-6} \text{ m}^2$) and the squared distance between source and sample (1/0.25 to 1).

Luminance of diffuse reflectance reference → reference for variation of illuminance across the sample / DUT surface

Alternatively, with the geometry of the measurement setup known, the illuminance across the DUT surface, $E(x, y)$ can be calculated according to the formula:

$$E(x, y) = \frac{I \cdot d_s}{\left(\sqrt{d_s^2 + (x - x_s)^2 + y^2} \right)^3}$$

with the isotropic luminous intensity of the source, I .

With this formula the variation of the illuminance across the DUT surface can be compensated.



5.2 Colorimeter data import

The BSDF-Meter software loads the PSF data into **three tristimulus channels** (TSC: X, Y, Z) and after definition of the geometry parameters the PSF is transformed into the *bidirectional scatter distribution function*, BSDF.

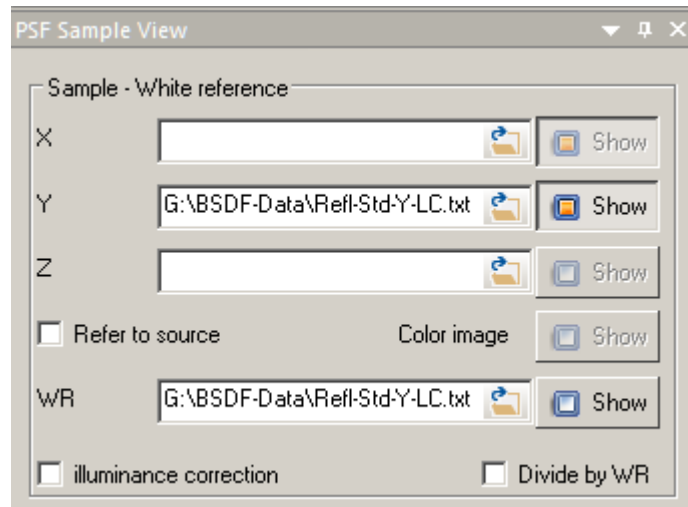


Figure 11: Dialog box for loading of the chromaticity data of the sample and of the white reference (WR - luminance data only).

The data format expected by the software is the format of the colorimeter data file as obtained by export to ASCII. The file extension is *.txt. Any other data file format than that provided by the colorimeter software will be rejected and cause an error message.

The intensity of each *tristimulus channel* (TSC) can be displayed separately and if the required 3 components (TSCs) are loaded (X, Y, Z), the PSF can be displayed as a *color image*.

The sample data can be related to the light source for evaluation of transmittance and reflectance ratio (i.e. ratio of transmitted or reflected luminance with respect to the source luminance).

The sample data can be corrected for the variation of the illuminance across the area included in the measurement by selection of the feature [Divide by WR]. This activates division of the sample data set by the **luminance** reflected from the white reflectance reference plate. That luminance array is normalized to the value at the location of the peak position of the sample.

Alternatively, the DUT three tristimulus channels (TSC: X, Y, Z) can be corrected for the variation of the illuminance across the DUT surface area numerically according to the formula:

$$E(x, y) \approx \frac{d_s^3}{\left(\sqrt{d_s^2 + (x - x_s)^2 + y^2}\right)^3} \quad 0 \leq E(x, y) \leq 1$$

This numerical correction is activated by checking of the tick box [illumination correction].



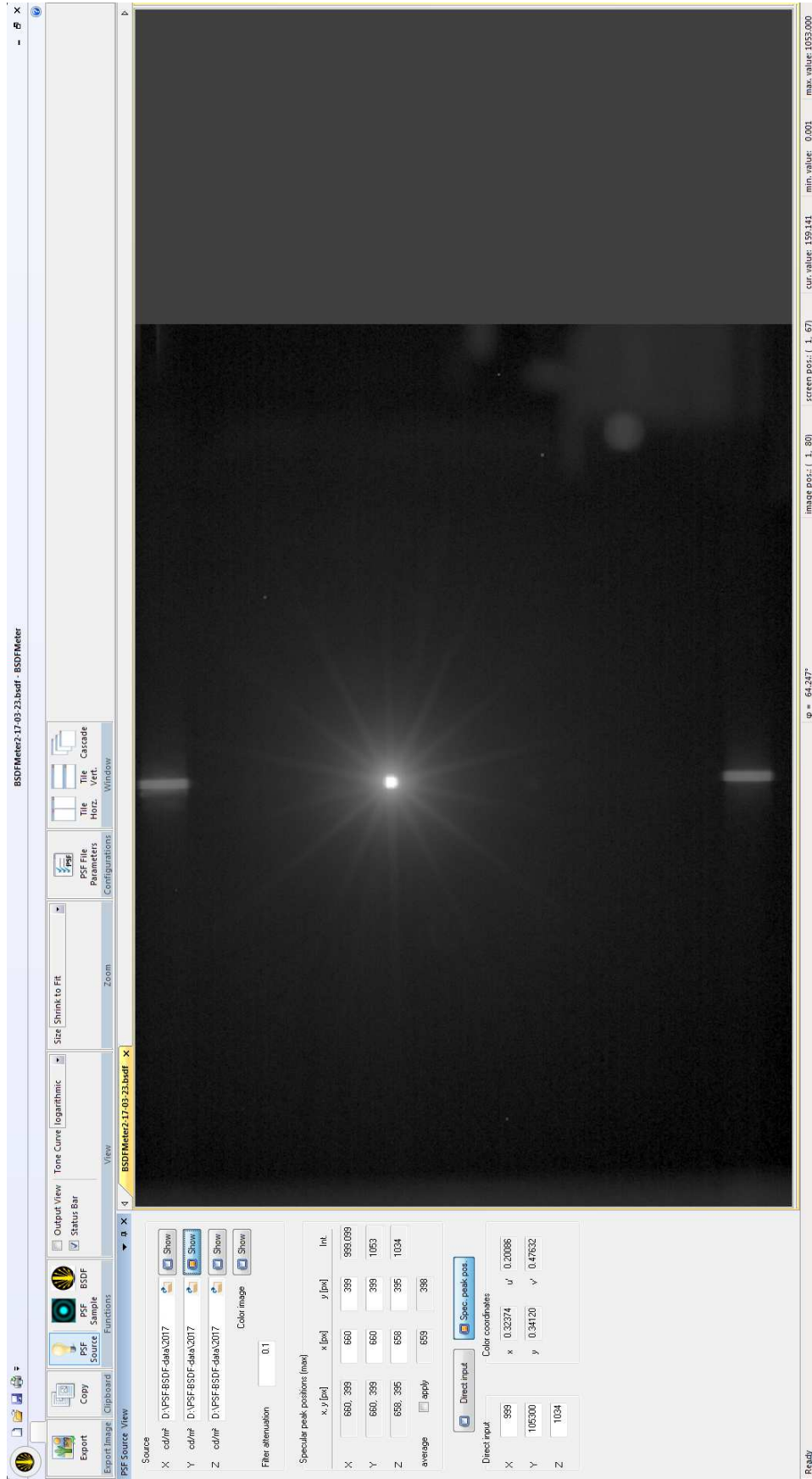


Figure 12: BSDF-Meter Software in PSF-Source view mode.



5.3 PSF-Source View

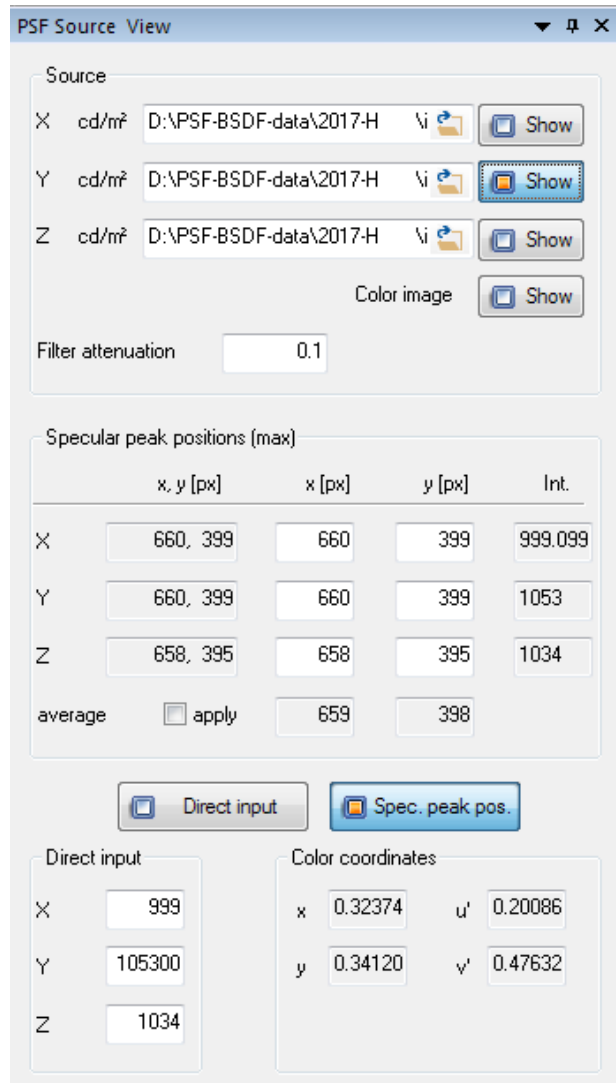


Figure 13: Dialog boxes for data input (tristimulus channels X, Y, Z), specification of the filter attenuation (<1) and output of the respective peak positions.

After loading of the tristimulus channels (TSC), X, Y, Z, a color image of the light source can be displayed with linear and logarithmic intensity scaling. Please note that logarithmic scaling does not correctly reproduce colors, **it is provided for visual inspection of low intensity parts of the image.**

The software determines the location of the peak values of the three channels and displays the respective positions in terms of iLMD pixels. An average is calculated from the individual peak locations that can be applied by operator selection (recommended). The X, Y, Z values from the respective peak locations are used as reference values for the subsequent evaluations.

Measurement of the source may require a neutral density filter (e.g. with thin metal films) to attenuate the high luminance of the light source and thus to avoid overexposure of the iLMD. Alternatively, the chromaticity of the light source can be evaluated with an achromatic diffuse reflectance reference plate located at a short distance to the source.

The chromaticity evaluated in that way may be entered manually after activation of the **Direct Input** button. The filter attenuation is not effective for the direct input option.



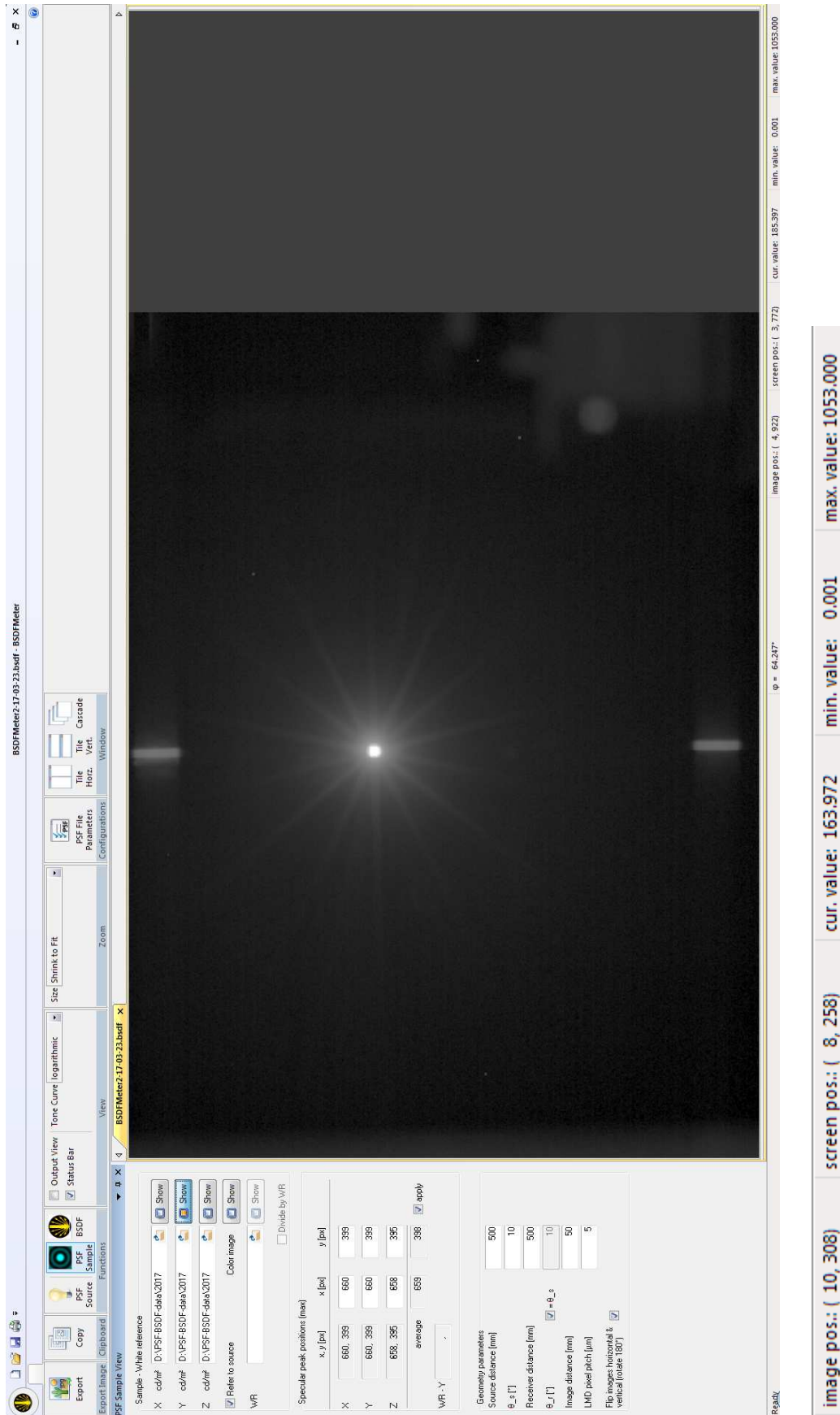


Figure 14: BSDF-Meter Software in PSF-sample mode.

The status listing displays the position of the cursor in iLMD image and display screen coordinates together with the current value, maximum and minimum value of the image data.



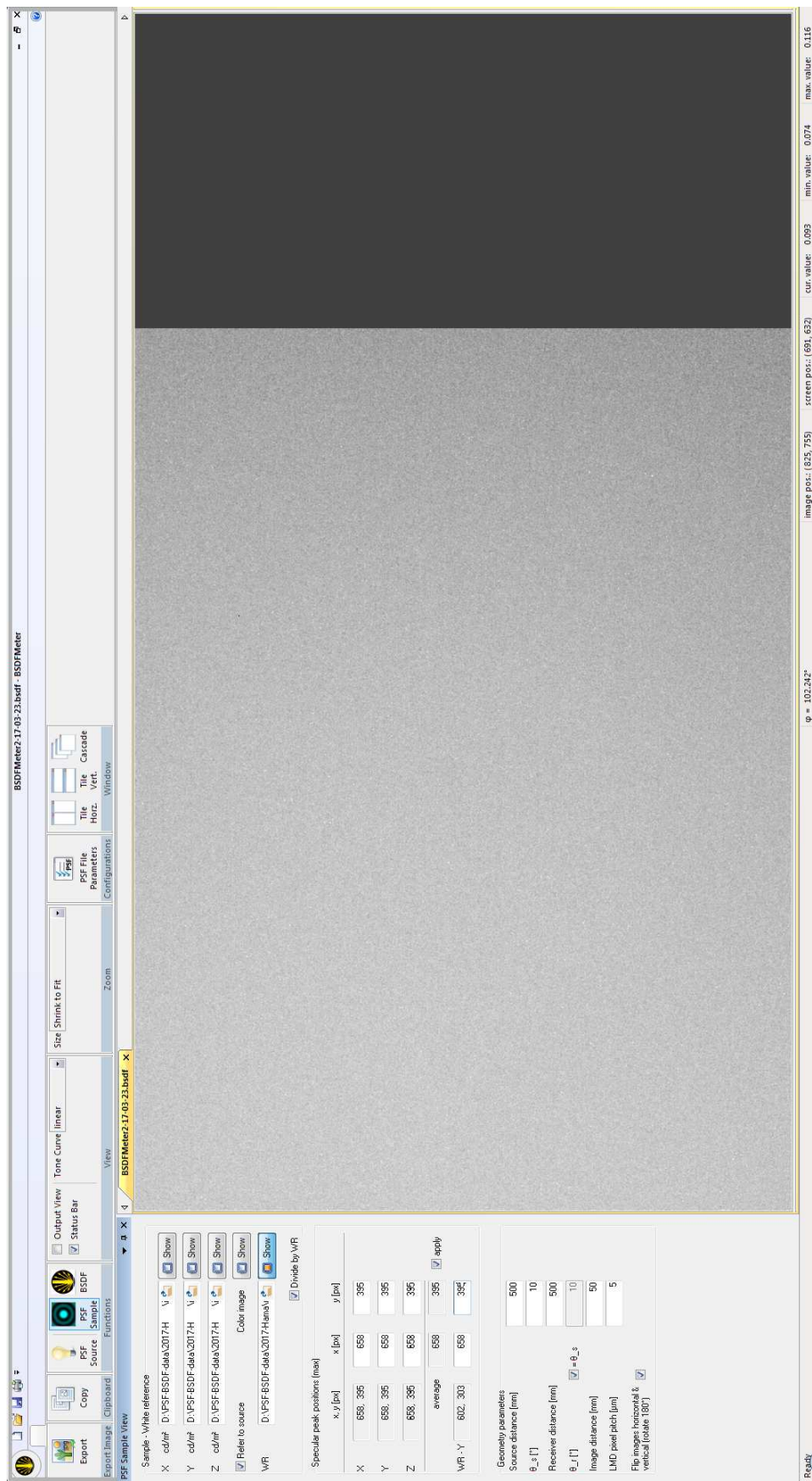


Figure 15: BSDF-Meter Software in PSF-sample mode showing the luminance distribution of the white reflectance reference panel.



5.4 PSF Sample View

PSF Sample View

Sample - White reference

X cd/m² D:\PSF-BSDF-data\2017-H Show

Y cd/m² D:\PSF-BSDF-data\2017-H Show

Z cd/m² D:\PSF-BSDF-data\2017-H Show

Refer to source Color image Show

WR D:\PSF-BSDF-data\2017-H. Show

Divide by WR

Specular peak positions (max)

	x, y [px]	x [px]	y [px]
X	658, 395	658	395
Y	658, 395	658	395
Z	658, 395	658	395
average		658	395
WR - Y	602, 303	658	395

apply

Geometry parameters

Source distance [mm] 500

θ_s [°] -10

Receiver distance [mm] 500

θ_r [°] = $-\theta_s$ 10

Image distance [mm] 50

LMD pixel pitch [µm] 5

Flip images horizontal & vertical (rotate 180°)

Figure 16: Dialog boxes for data input (chromaticity channels X, Y, Z) and output of the respective peak positions.

After loading of the tristimulus channels, X, Y, Z, a color image of the sample can be displayed.

The BSDFmeter software automatically determines the location of the peak value of the three channels and displays the respective positions in terms of iLMD pixels. An average is calculated from the individual peak locations that can be applied by operator selection (recommended). Since the white reference does not exhibit a distinct peak, the peak position can be taken over from the sample.

The luminance value at the "peak position" of the data from the white reflectance reference is used for normalization of the WR (white reflectance) data set.



The BSDF-Meter Software automatically determines the location of the maximum intensity of the three PSFs which usually coincides with the specular direction. If there are significant differences in the location of the individual specular direction (this may happen in the case of samples with pronounced scattering), the locations can be entered manually by the operator.

In the case of strong scattering of the sample the specular peak cannot be detected easily in the recorded image. In that case the specular direction can be determined by enhancing specular reflection by placing a thin smooth (i.e. non-scattering) layer on top of scattering samples (e.g. microscope cover glass).

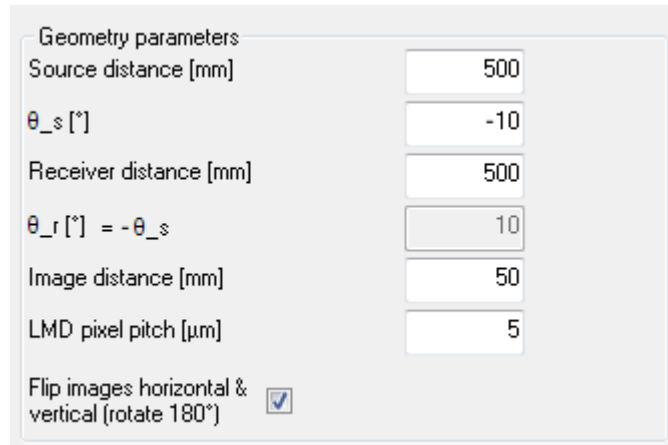


Figure 17: Dialog box for specification of the geometry of the BSDF setup.

The distance between the point light source and the DUT, s , and the LMD and the DUT, r , can be measured directly, the angle of light incidence and the LMD inclination are obtained from the geometry as illustrated in Fig. 19.

The pixel pitch of the CCD detector array of the colorimeter is specified in the technical data sheet of the instrument.

The **image distance**, b , is calculated from the magnification, M , and the distances d_r and d_s as follows.

$$M = \frac{h_i}{h_o} = \frac{b}{d_r + d_s} \quad b = \frac{h_i(d_r + d_s)}{h_o}$$

with h_i image height,
 h_o object height.

The image height, h_i , is the number of detector array pixels per object height (in terms of pixels) as evaluated with the colorimeter control and evaluation software multiplied with the pixel pitch of the detector array of the colorimeter. More details on this procedure are given below.

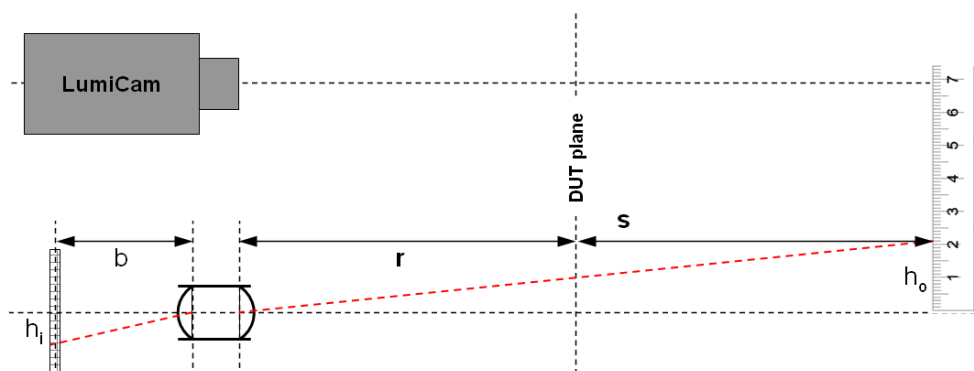


Figure 18: Sketch of imaging geometry of the light measurement device (LMD).



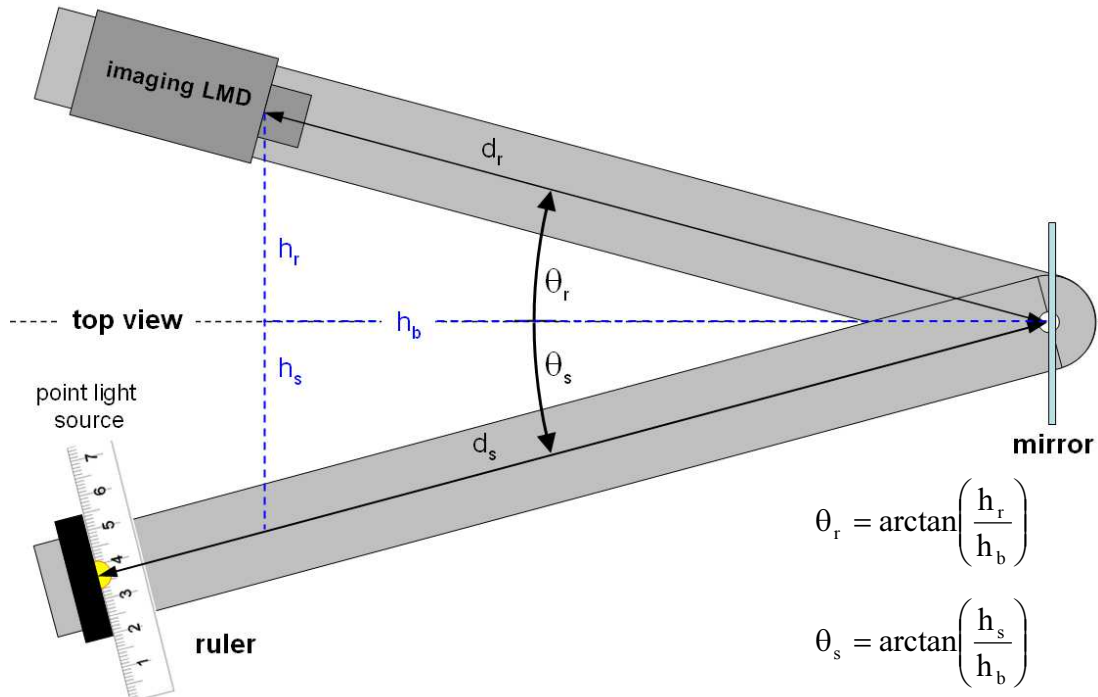


Figure 19: Setup for determination of the geometry parameters with a plane mirror.

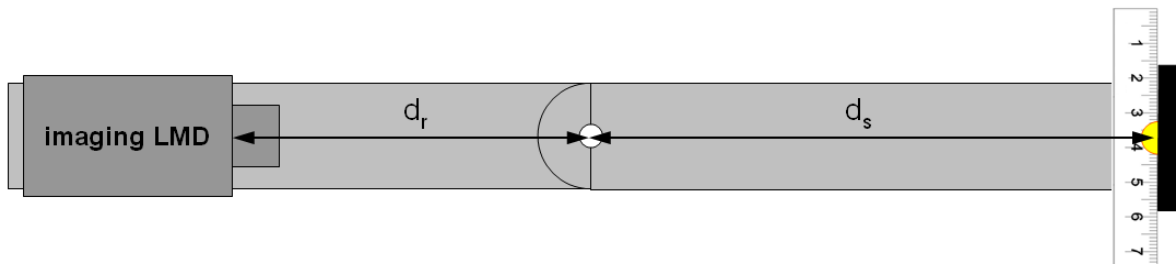


Figure 20: Unfolded setup for determination of the geometry parameters.



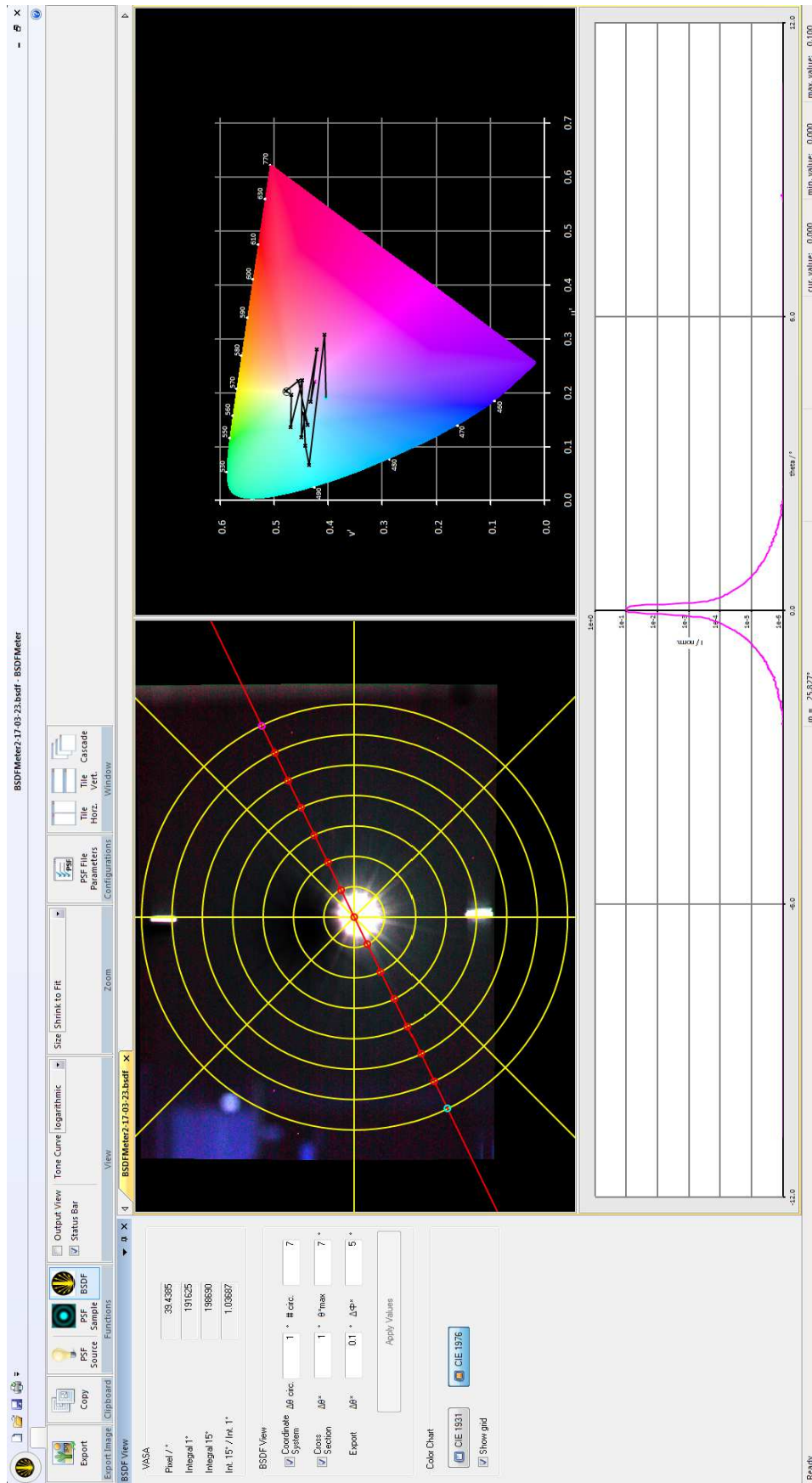


Figure 21: BSDF-Meter Software in BSDF mode.

The variation of transmitted or reflected luminance with angle of inclination, θ^* and azimuth, ϕ^* , is shown in the polar coordinate system. The variation for one specific azimuth angle given by the red diameter is shown in the cartesian coordinate system.



5.5 BSDF view

After successful transformation of the PSF data the center of the polar coordinate system with the spherical angles θ^* and ϕ^* should be located at the position of the specular peak.

With the first click into the window of the polar coordinate system, the cross-section is defined and shown by a red diameter. Now also the variation of transmittance or reflectance with angle of inclination, θ^* , is shown in the cartesian coordinate system for the azimuth angle that has been selected by clicking into the polar coordinate system.

BSDF View

Coordinate System $\Delta\theta$ circ. 1 ° # circ. 7

Cross Section $\Delta\theta^*$ 1 ° θ^* max 7 °

Export $\Delta\theta^*$ 0.1 ° $\Delta\phi^*$ 5 °

Apply Values

Color Chart

CIE 1931 CIE 1976

Show grid

Figure 22: Dialog box for specification of the parameters of the polar coordinate system.

The angular distance of the concentric circles and their total number can be specified within the dialog box shown in Fig. 22. The same applies for increment and number of sampling locations on the cross-section (red diameter). The data grid for export of the data to file is defined in the next line.



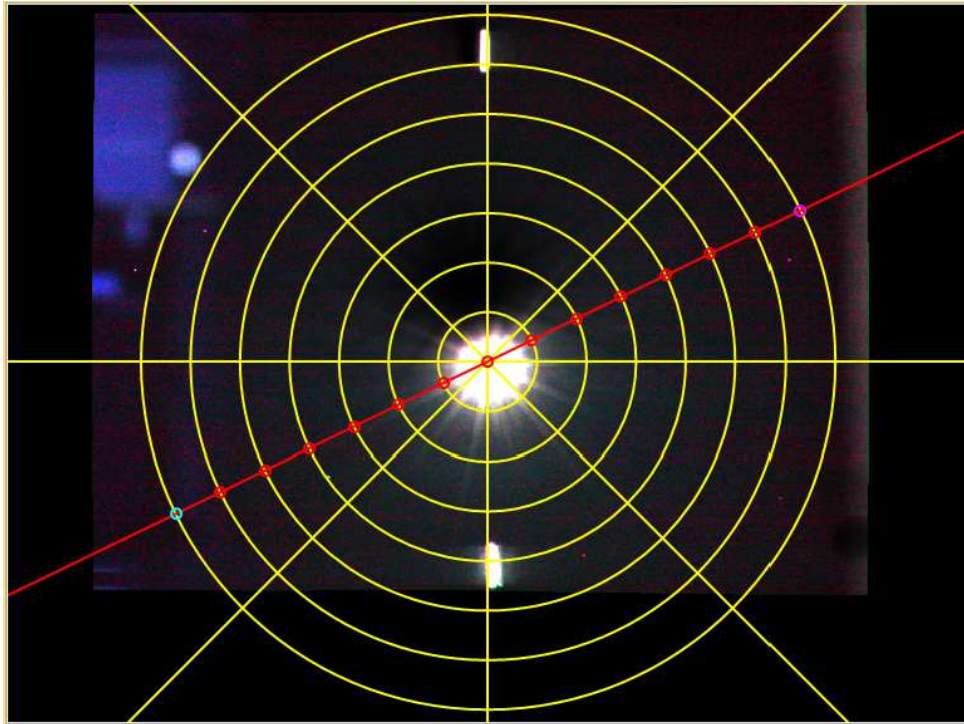


Figure 23: Polar coordinate system for presentation of the BSDF. The red diameter line specifies the azimuth of the cross-section shown below.

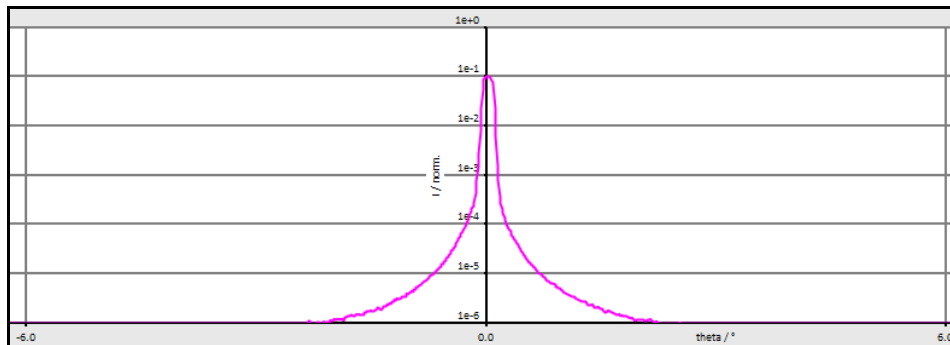


Figure 24: Variation of luminance with angle of inclination along the red line diameter shown in the polar coordinate system.

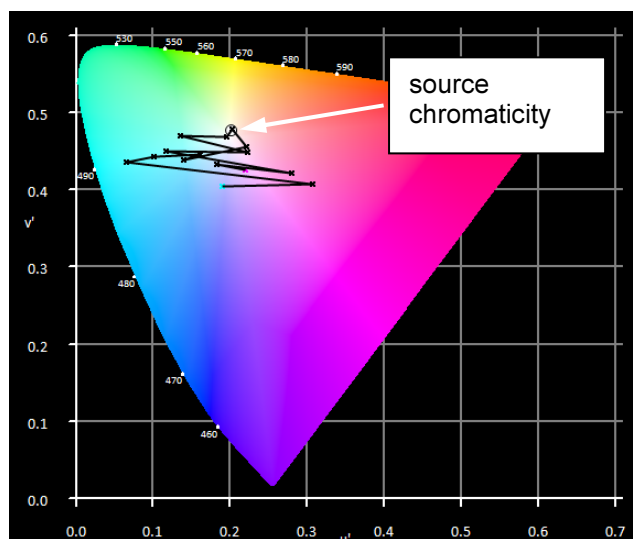


Figure 25: Variation of chromaticity (u' , v') with angle of inclination along the cross-section. The small circle indicates the chromaticity of the light source.



5.6 Transmissive measurements

As illustrated in Fig.3, the specular beam, $PS^*(x,y)$ is identical for reflective and for transmissive illumination (light source S for reflective illumination, light source S' for transmissive illumination, the mode of measurement (reflective - transmissive) is not of importance for the BSDF-Meter software.

6 Literature references

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