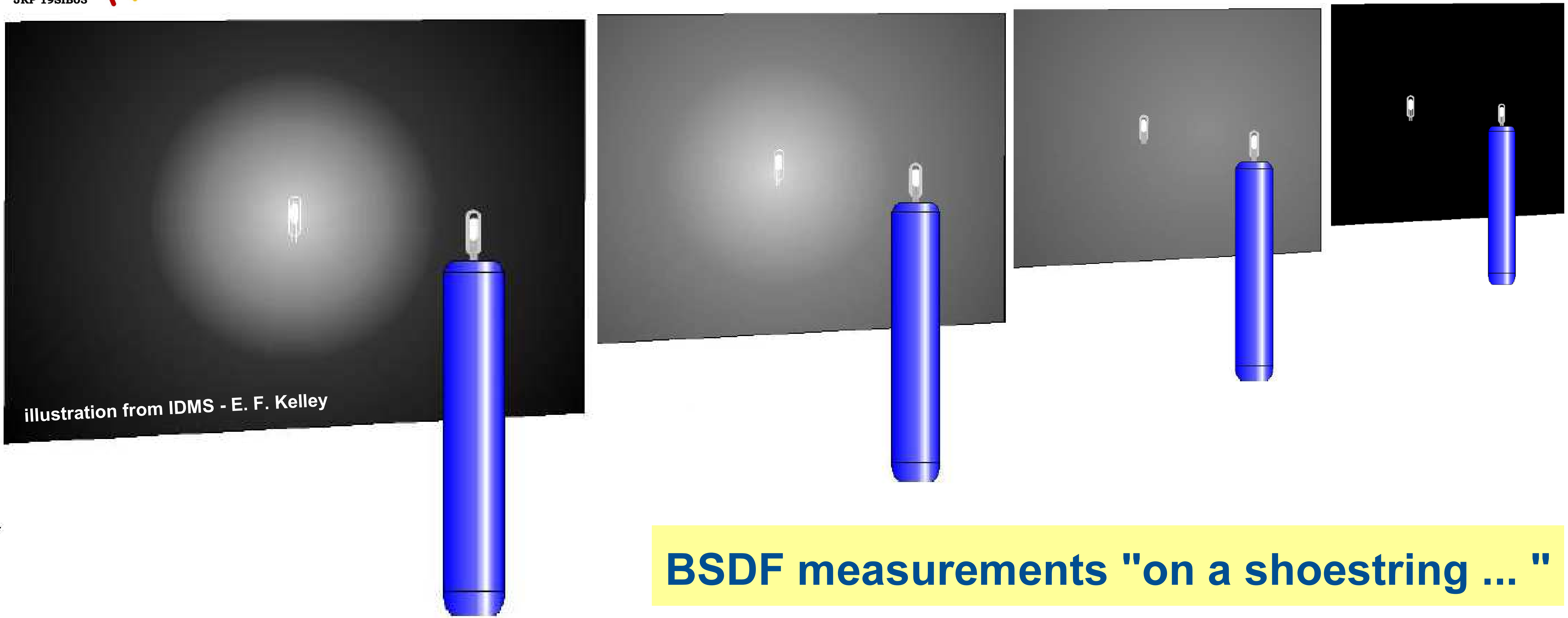
BxDiff
JRP 19SIB03

From the PSF to the BSDF ...

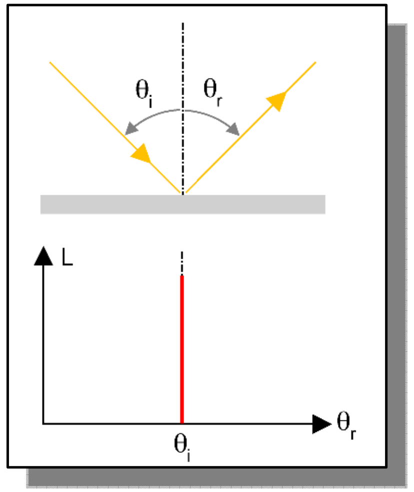


BSDF measurements "on a shoestring ... "

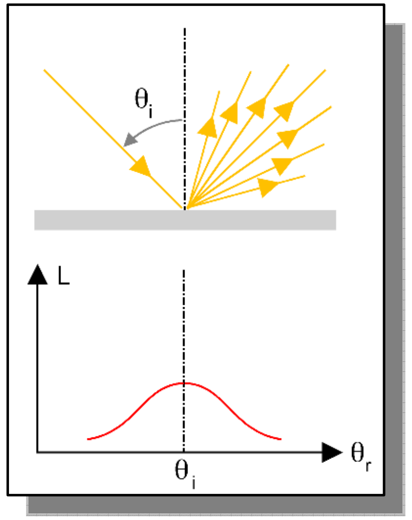
Michael E. Becker

Display-Messtechnik&Systeme - Rottenburg am Neckar - Germany

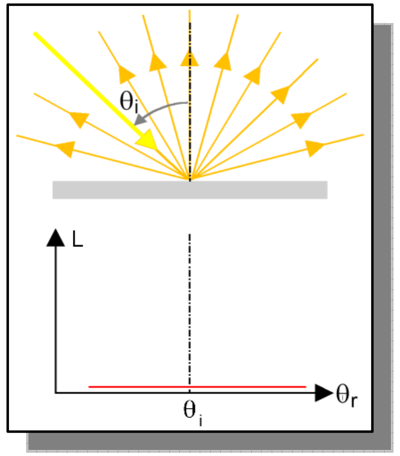
mirror



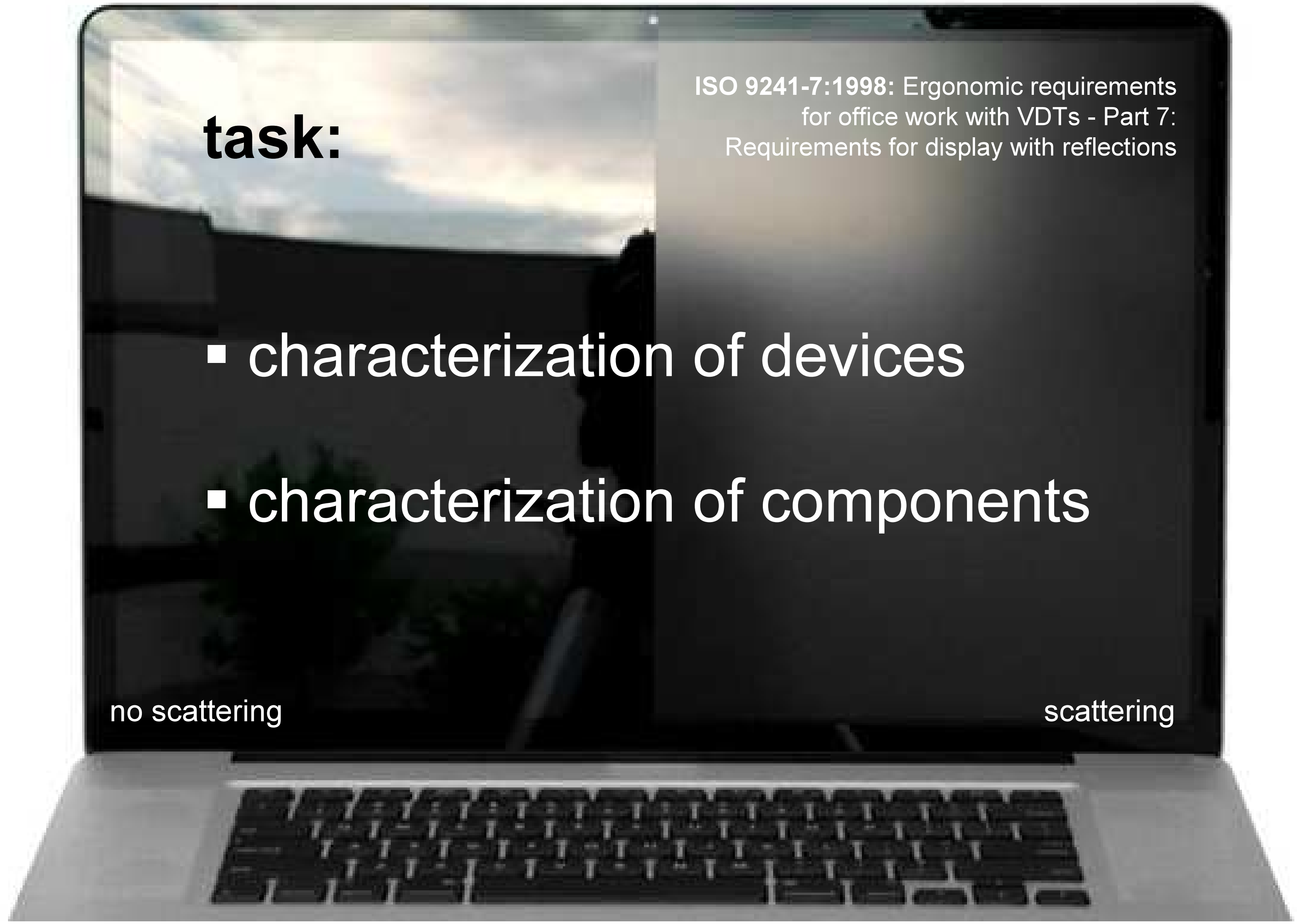
haze



Lambertian



scattering



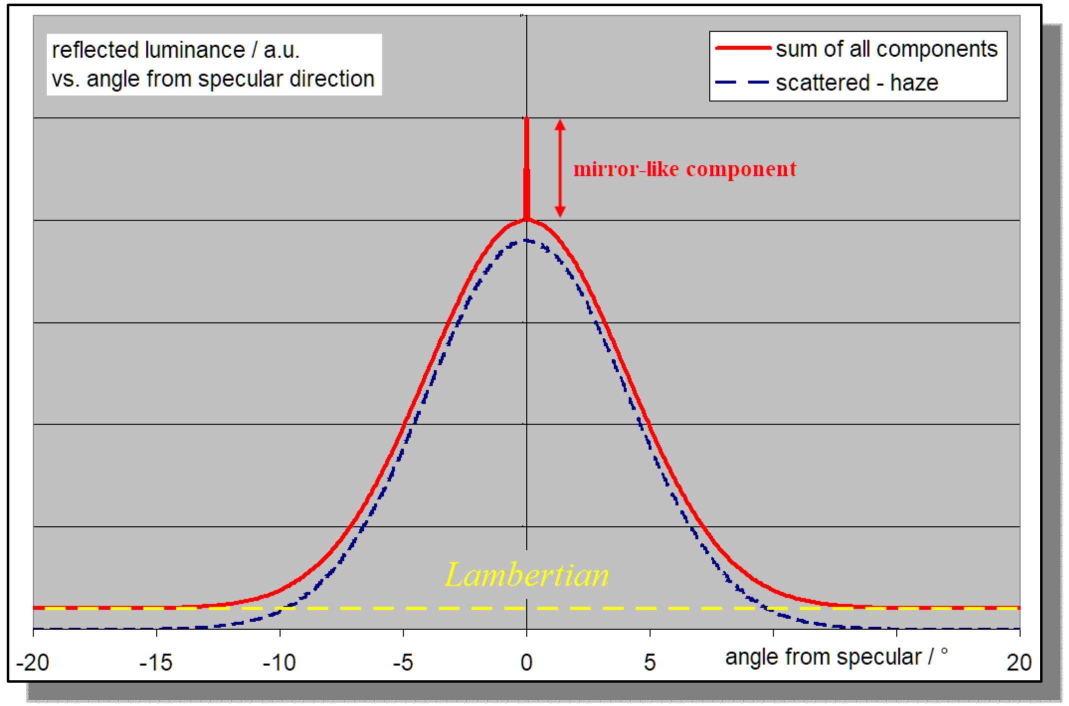
Disturbing and annoying effects of reflections form electronic displays have been taken serious since VDTs moved into office environments in the 1980s.
Interest for detailed characterization of display reflections emerged in the late 1980s.
"... to protect data entry workers and to maintain their performance levels"

The Components of Reflection

1998: E. F. Kelley and co-authors analyzed application of the ISO 9241-7 measurement setups to LCD monitors with **scattering AG-layers** causing haze and concluded, that the complications introduced by the haze asked for a new approach to characterization of the reflections of such displays.

The **luminance reflected by a display** in the direction of the LMD optical axis is the **sum of three components**:

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

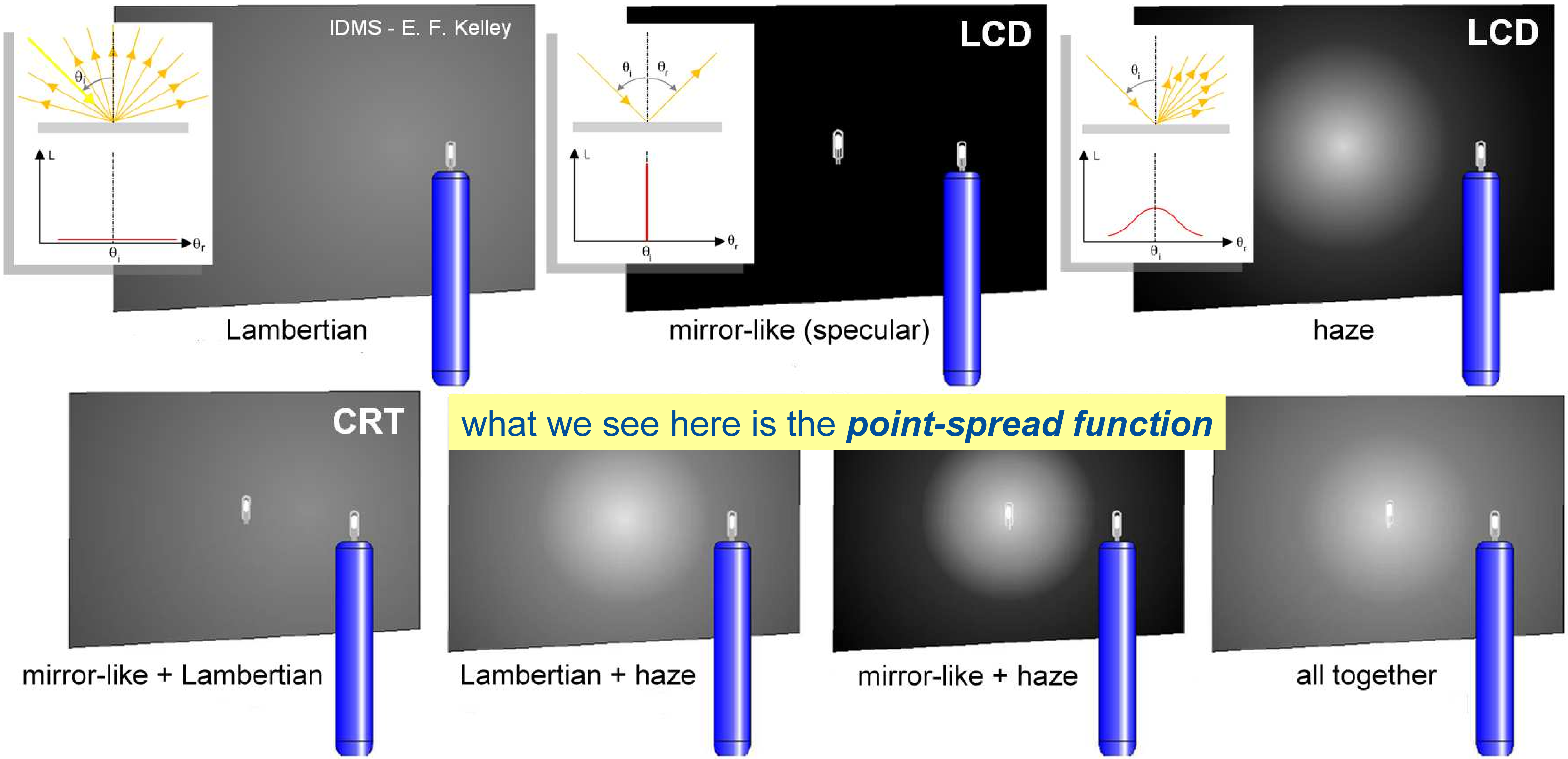


These 3 components are not mutually independent, the incident light flux is distributed among them depending on details of the sample properties and structure and on the measurement arrangement.

Once these basic reflection components are well characterized and specified, the luminance reflected in any direction of observation can be calculated for arbitrary arrangements of light sources in the surroundings of the display.

It is claimed that only on such a basis "ergonomists can make distinguishing evaluations that are reproducible and relevant to what the eye sees". **This turned out to be true ...**

The Components of Reflection



what we see here is the ***point-spread function***

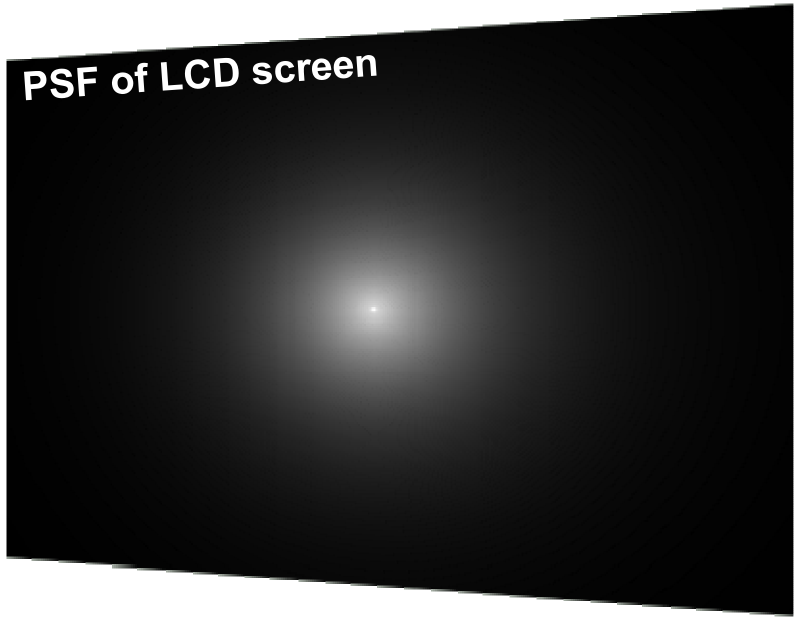
Measurement of Directional Light Distribution

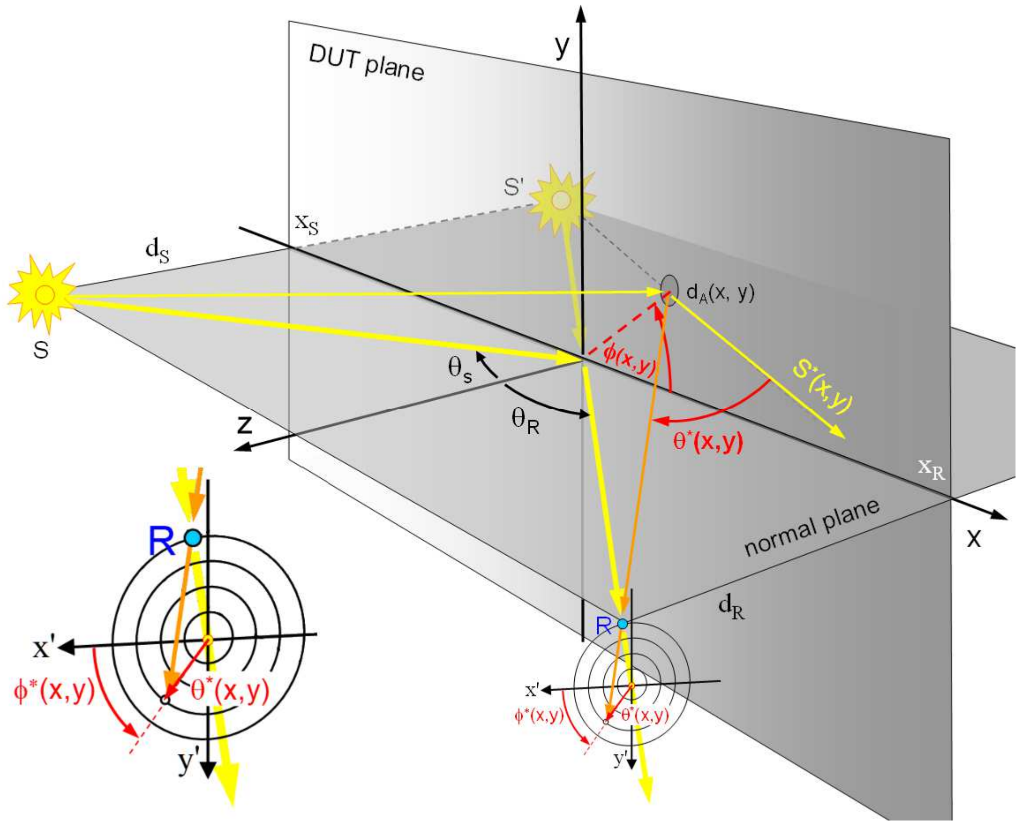
The directional distribution of light scattered during transmission and reflection can be evaluated by:

(1) motorized directional scanning (time-sequential),
(2) conoscopic imaging,
(3) catadioptric imaging,
(4) projection on a spherical screen.

These approaches are usually based on
- complex mechanical goniometer setups, or require
- arrangements with special optical components, e.g. (hemi)-spherical screens, spherical or elliptical mirrors, complex lens systems, etc.

Alternatively, directional scanning can be realized - in the case of planar samples illuminated by a point light source - by analysis of the lateral distribution of scattered light (i.e. ***point-spread function***, PSF).





Observation of the BRDF from the PSF, Dr. E.F. Kelley, private communication, 1997

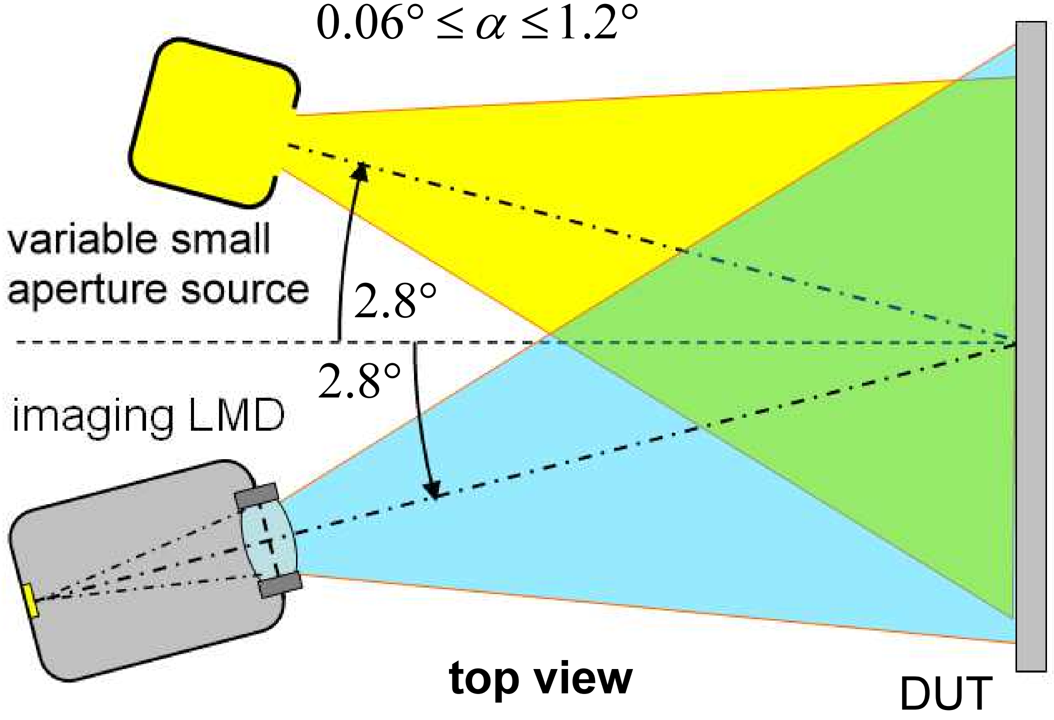
$$f_r(\theta_i,0,\theta_r,0) = L(x)\cdot r_i^2 / (L_s A_s \cos\theta_i)$$

K. F. Karner, et al.:"An Image based Measurement System for Anisotropic Reflection", Eurographics '96, 15,3 (1996)

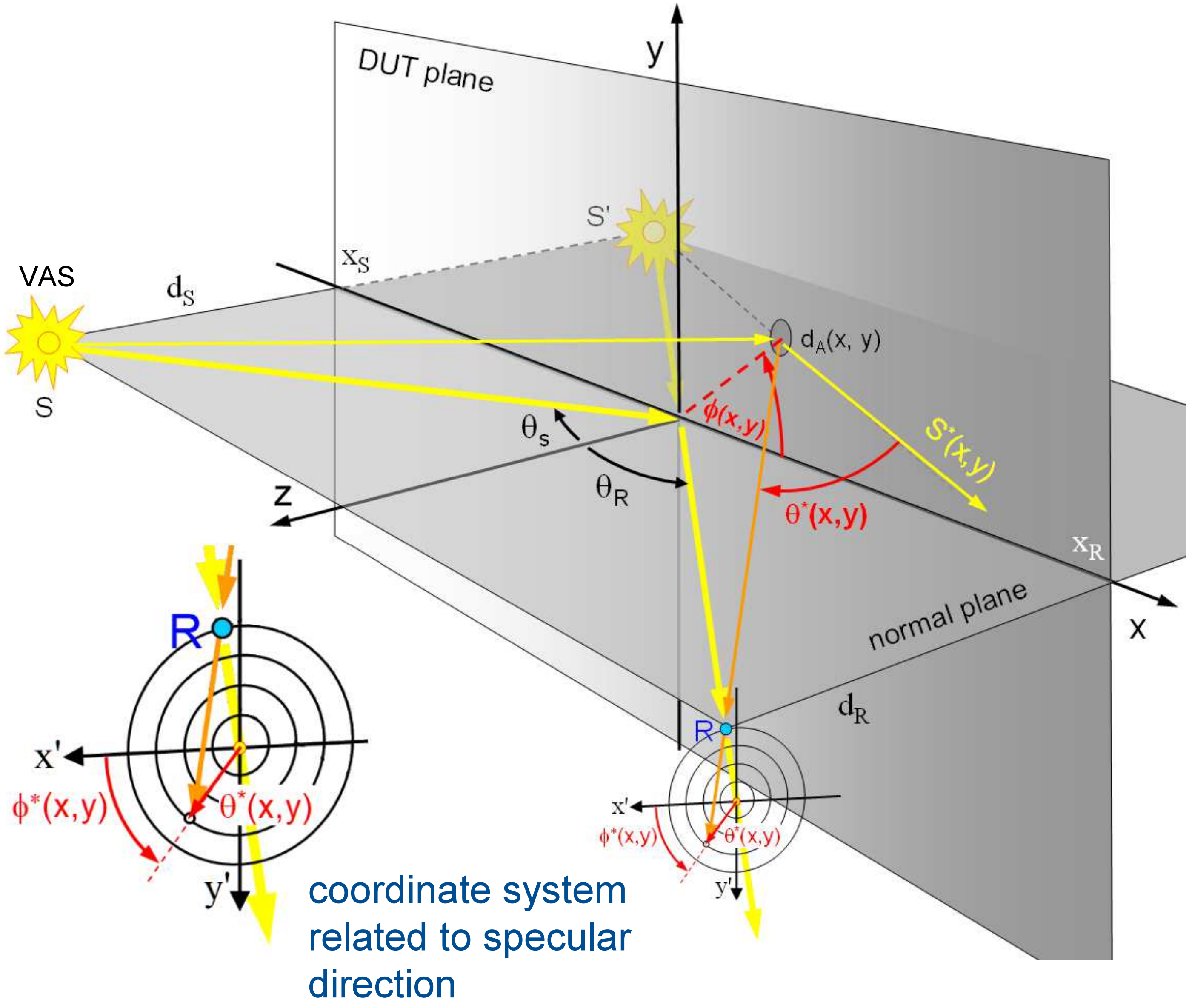
R. Lu, et al.: "Optical properties (bidirectional reflection distribution functions) of velvet", Appl. Optics, 37, 25(1998)
J.S. Arney: "An Inexpensive Micro-Goniophotometry You Can Build", IS&T's 1998 PICS Conference

F. B. Leloup, et al.: Rapid determination of the photometric bidirectional scatter distribution function by use of a near-field goniophotometer, SPIE 2014

From the PSF to the BSDF



Measurement setup for reflection and transmission

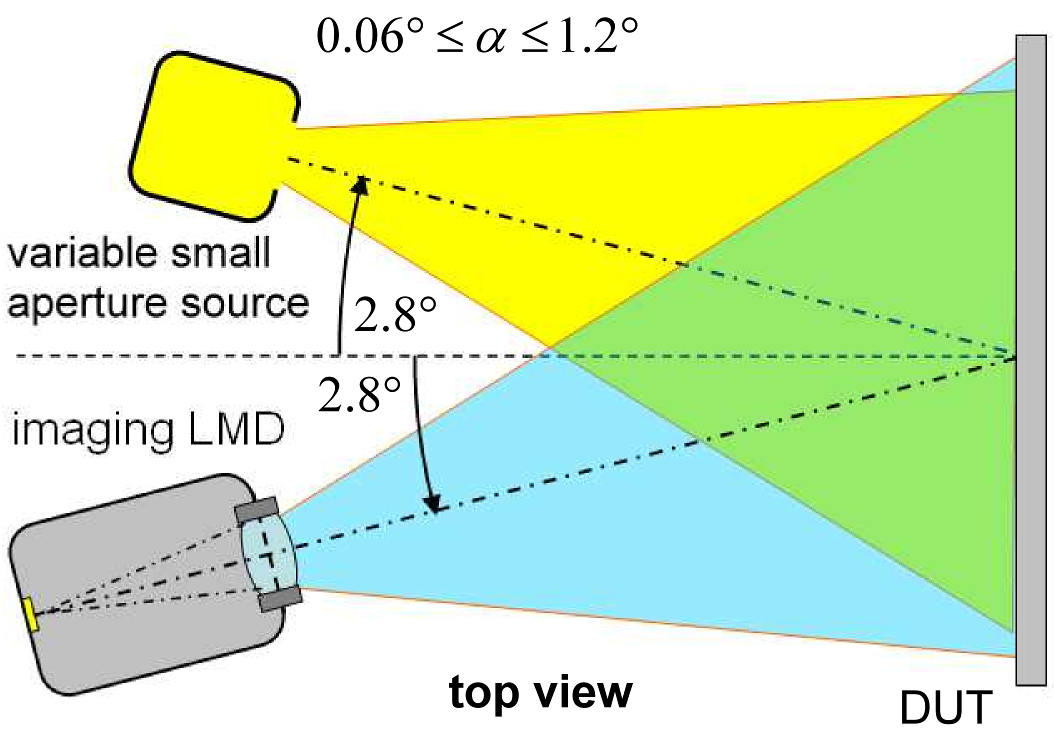


For each luminance sample of the LMD detector array, I(x',y'):

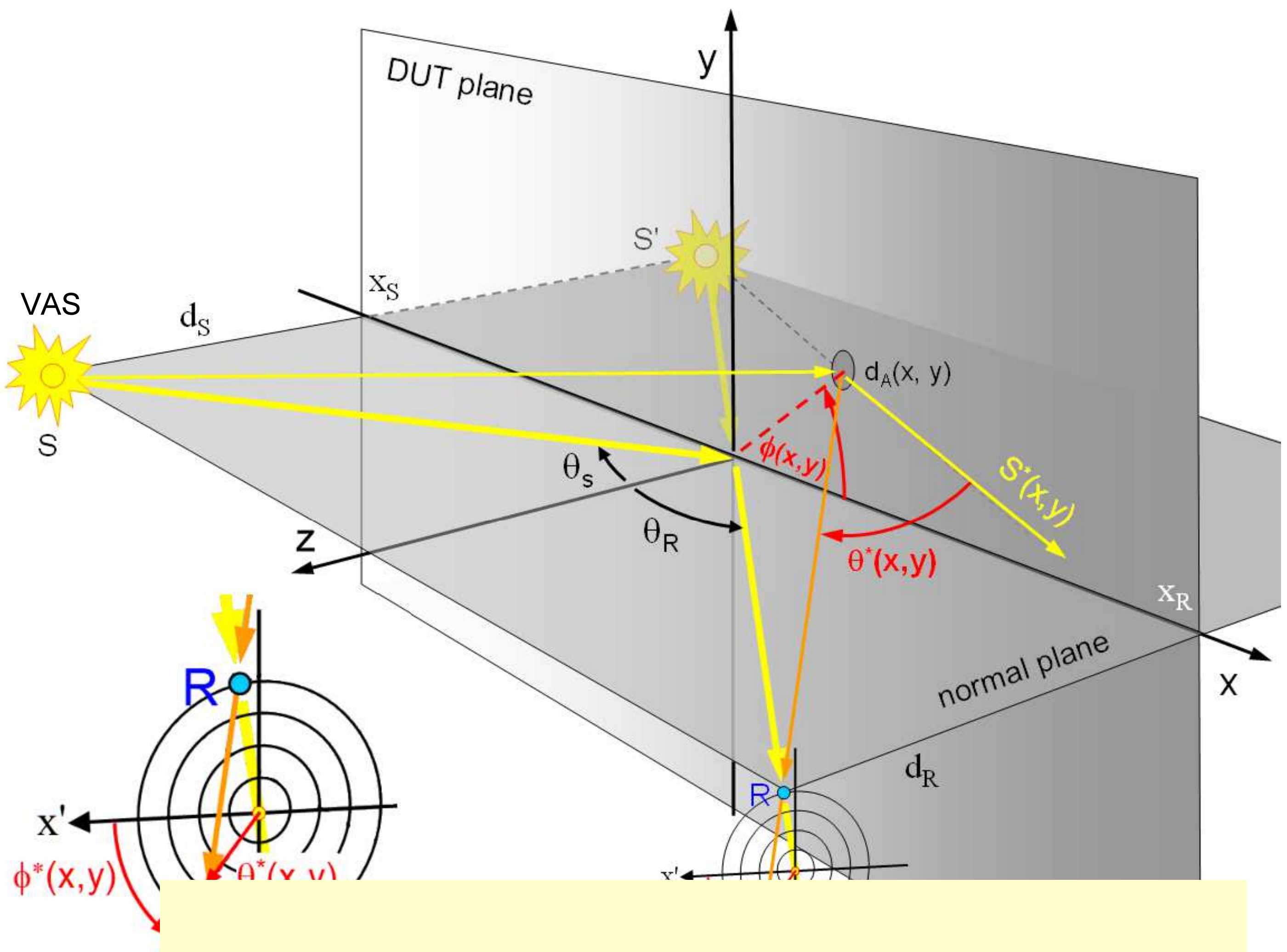
- calculate the position of the area element dA(x, y) on the DUT,
- for each area element dA(x, y) on the DUT:
  - calculate direction of light incidence, (θ_i, ϕ_i),
  - calculate direction of received light, (θ_r, ϕ_r),
  - calculate illuminance E(x, y),
- calculate angles with respect to the specular beam, θ^* and ϕ^*
- calculate $I^*(\theta^*, \phi^*) = I(\theta^*, \phi^*) / E(\theta^*, \phi^*)$

➲ arrange $I^*(\theta^*, \phi^*)$ obtained from I(x', y') into a polar coord. system.

From the PSF to the BSDF



Measurement setup for reflection and transmission



For each luminance sample of the LMD detector array, I(x',y'):
 calculate the position of the area element dA(x, y) on the DUT,
 for each area element dA(x, y) on the DUT:
  calculate direction of light incidence, (θ_i, ϕ_i),
  calculate direction of received light, (θ_r, ϕ_r),
  calculate illuminance E(x, y),
 calculate angles with respect to the specular beam, θ^* and ϕ^*
 calculate $I^*(\theta^*, \phi^*) = I(\theta^*, \phi^*) / E(\theta^*, \phi^*)$

➲ arrange $I^*(\theta^*, \phi^*)$ obtained from I(x', y') into a polar coord. system.

mapping of angles based on shift-invariance of scattering (in dir. - cosine space) - Harvey

Conditions and Requirements

BRDF measurements: **fixed direction of light incidence** and with an **LMD scanning the directional variations** of light reflected from one area on the DUT (field of measurement).

PSF analysis: each area element on the DUT has one direction of light incidence and one direction of reflected light received by the LMD. PSF analysis provides valid results as long as the BRDF of the DUT does not change significantly with direction of light incidence.

Evaluation of the PSF to obtain an approximate BSDF is subject to the following **conditions**:

- the reflectance of the sample must be **uniform across the area** included in the measurement (this is realized well by display screens and their components),
- the **angle of light incidence should be small** to keep variations of the Fresnel coefficients low (e.g.: <20°),
- the **angle of inclination** with respect to the specular direction, θ^*, should be **restricted to about 20°**.

Measurements:

- VAS aperture adjustments are made manually and the settings are evaluated by measurement of the ***VAS aperture diameter*** via a non-scattering mirror.
- The ***sample illuminance*** is evaluated via the luminance reflected by a ***calibrated diffuse reflectance standard***.
- The linear relationship between source aperture area and illuminance is evaluated and checked.

For each setting of the source aperture
three luminance images are recorded:

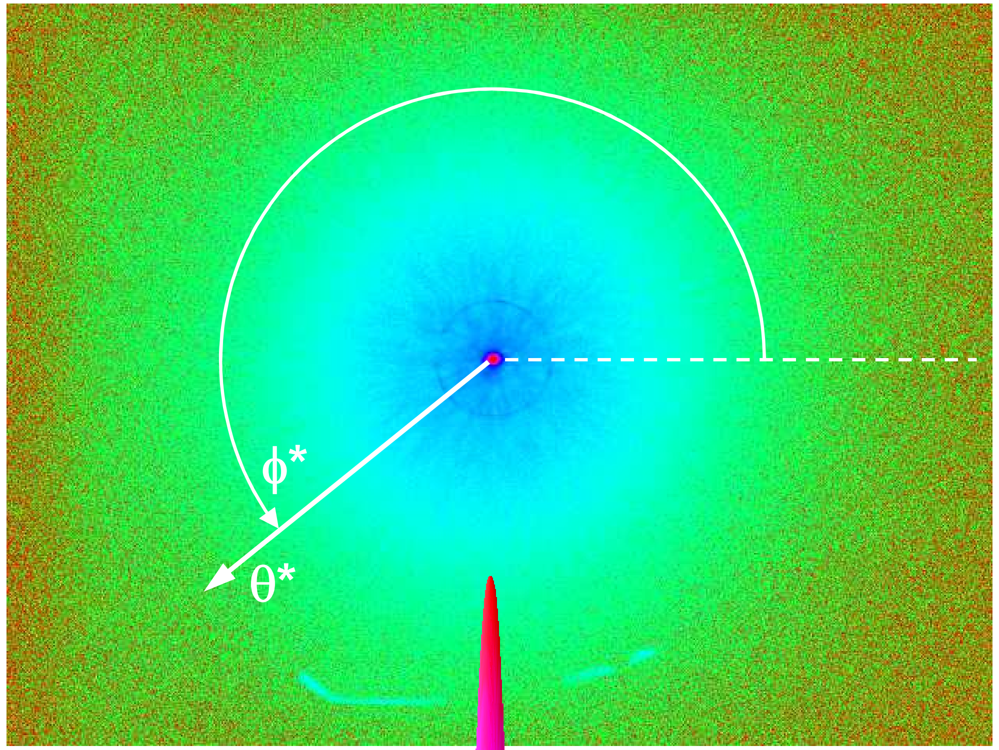
1. image of the sample (DUT);

2. image of the source aperture via a calibrated mirror (polished black glass) for evaluation of the **source aperture dimension** and for the **luminance distribution across the source aperture;**

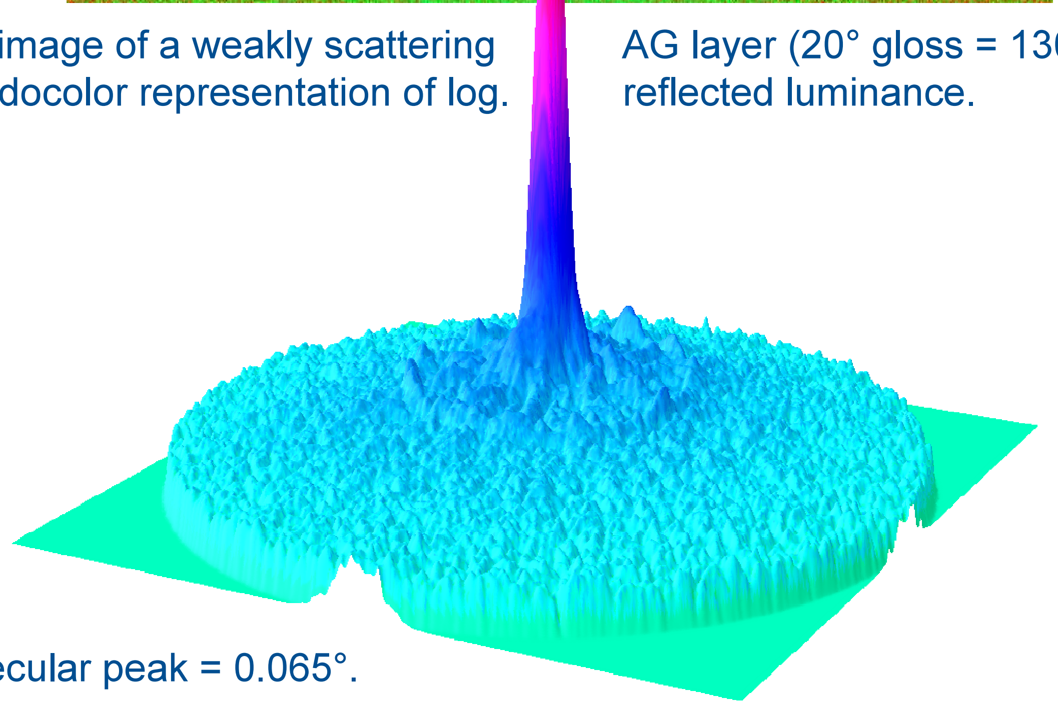
3. image of a calibrated diffuse reflectance standard (CIE: *perfect reflecting diffuser*) for **evaluation of the illuminance of the DUT**.

Luminance or tri-stimuls images are obtained as an average from a series of >25 individual images for reduction of noise;
HDR images can be assembled from a series of images taken with different exposure time settings.

The dynamic range of the images is limited by stray light of the LMD optical system to ratios between some 10^{+3} and 10^{+4} (~4,800 in this example).

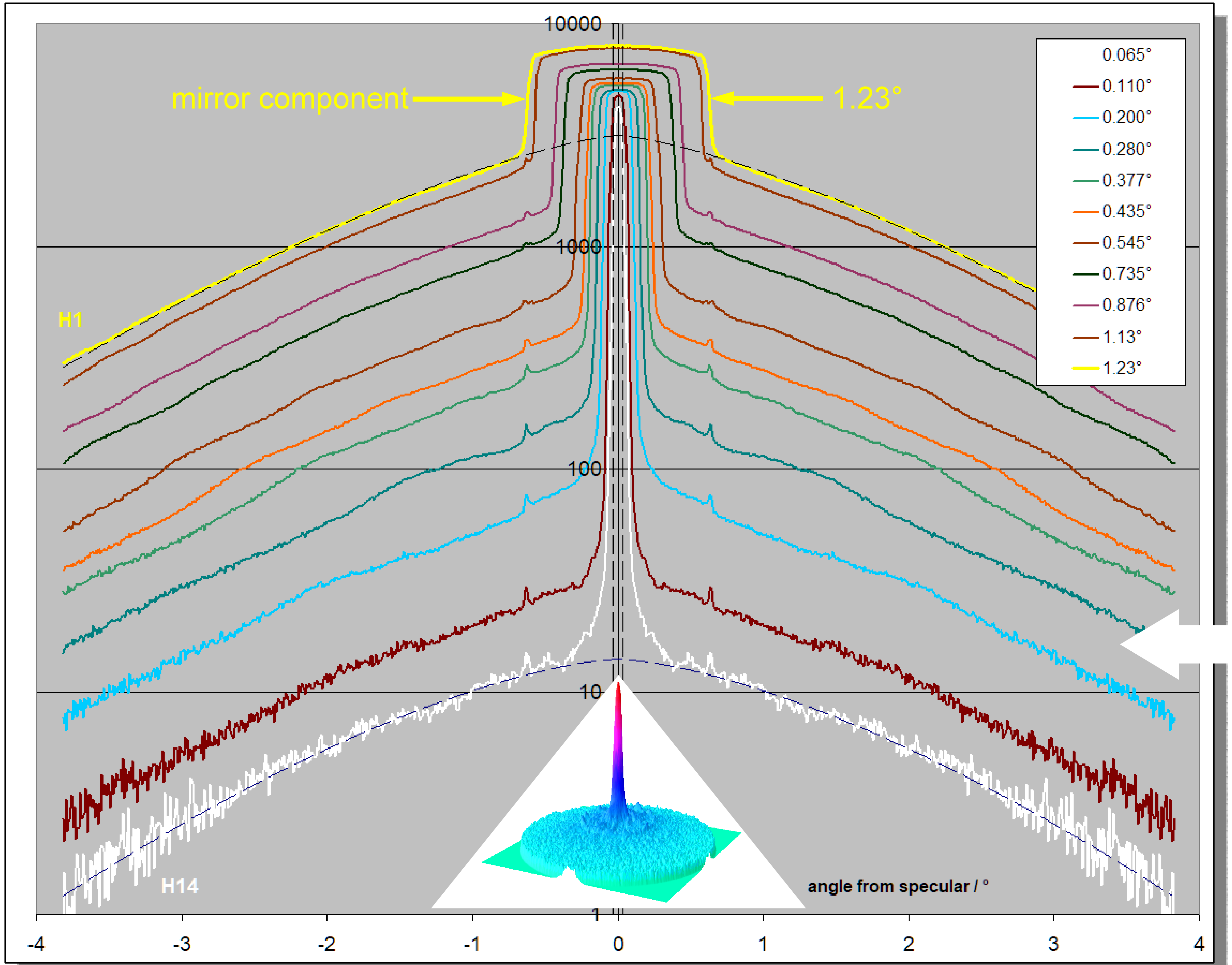


PSF image of a weakly scattering AG layer (20° gloss = 130).
Pseudocolor representation of log. reflected luminance.



FWHM of specular peak = 0.065°.

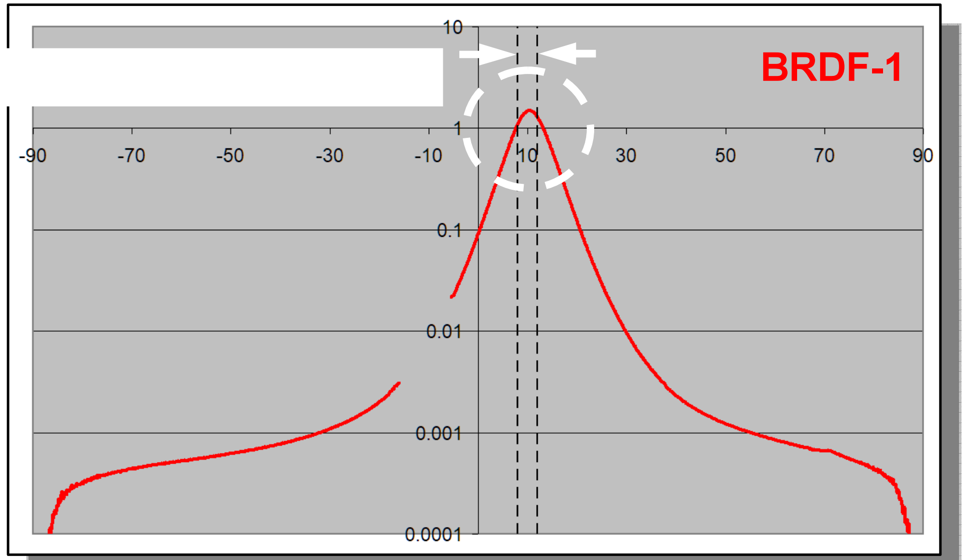
Evaluations



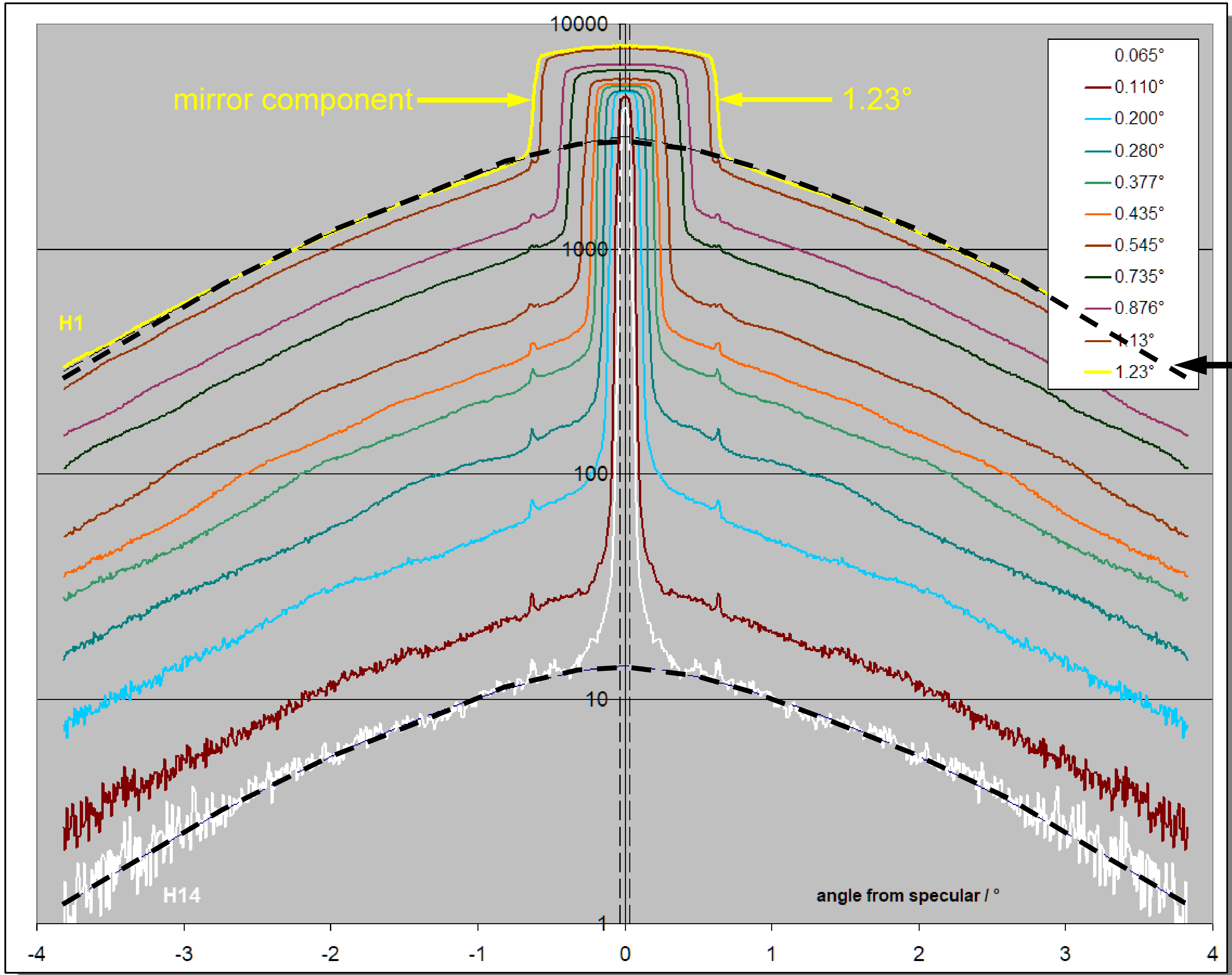
Family of reflectance distribution functions (BRDFs) illustrating variations with source aperture diameter ~ illuminance.

BRDF of the same DUT over ±90°

No distinct Lambertian component can be identifed, no mirror-like component either. The source-receiver signature FWHM is 3.5° Gaußian.



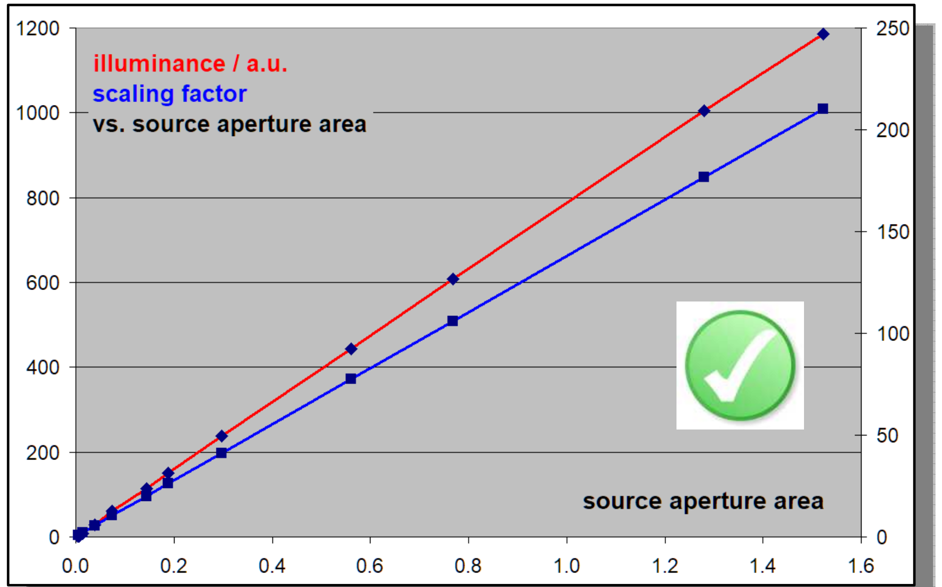
Evaluations

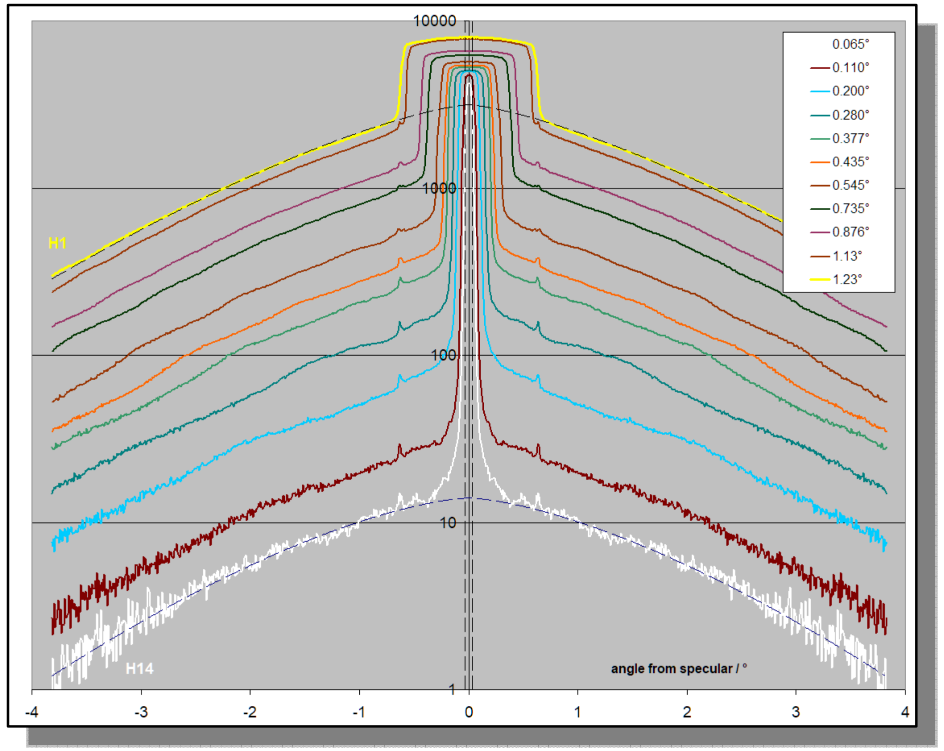


Family of reflectance distribution functions (RDFs) illustrating variations with source aperture diameter ~ illuminance.

The haze component is fitted to a Lorentz function (- - -) with constant shape via a variable scaling factor.

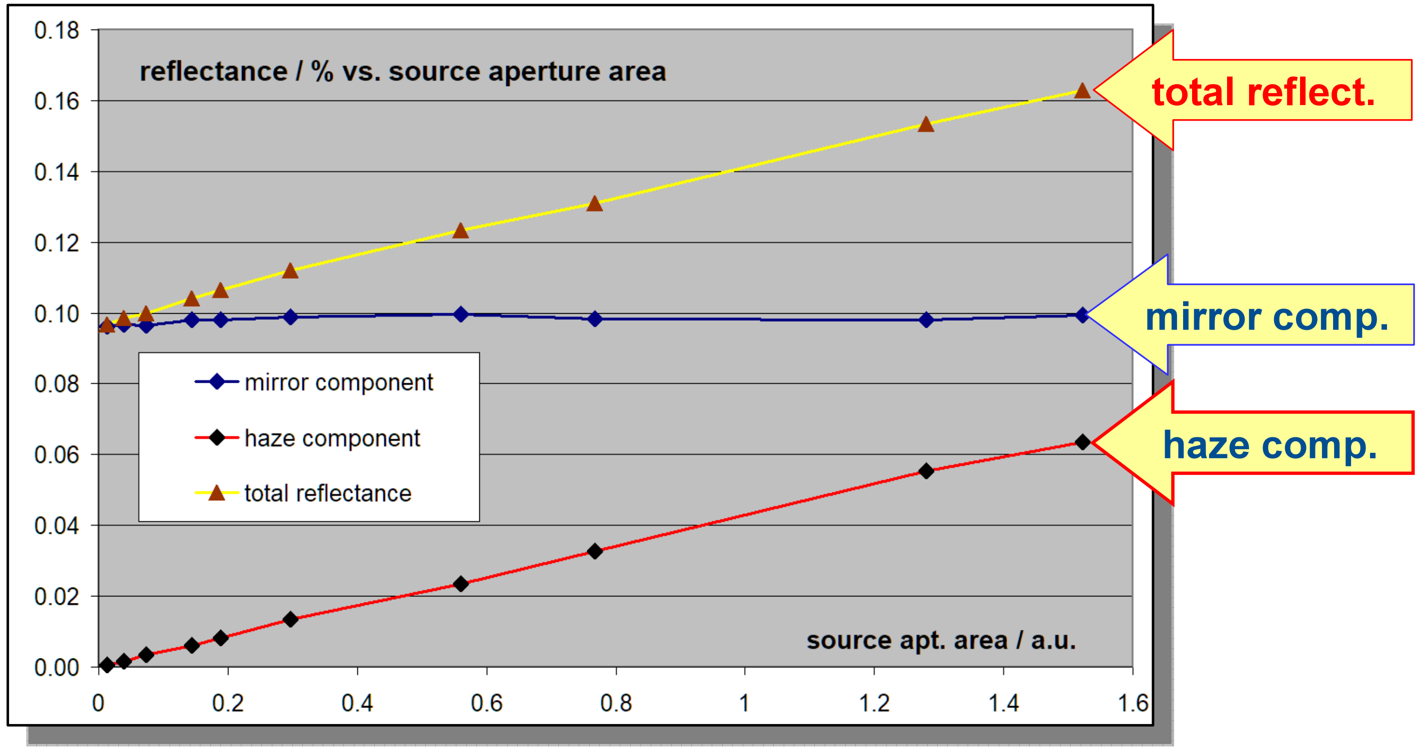
The scaling factor is proportional to the source aperture area and to the measured illuminance levels.



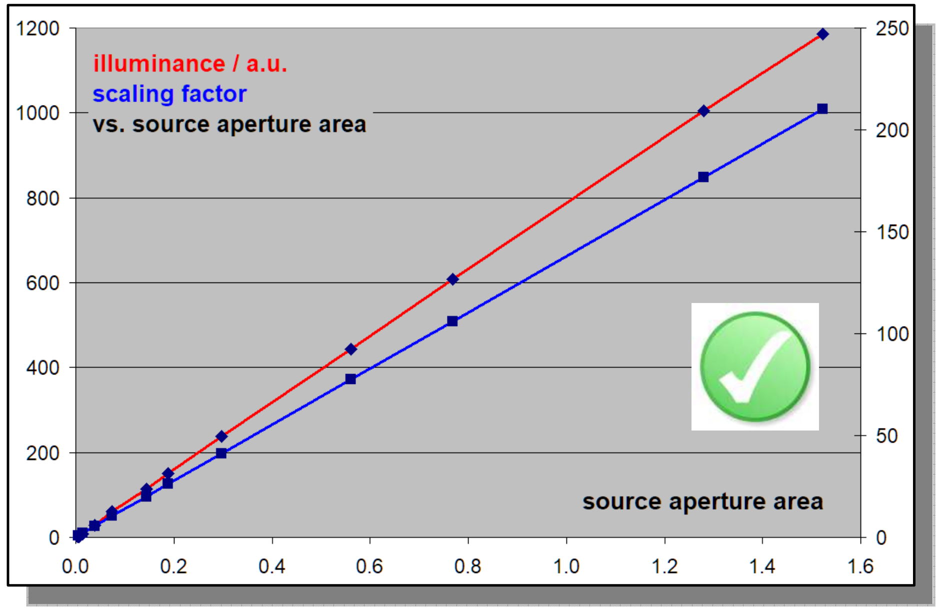


BRDF vs. illuminance

evaluation



diagnostic

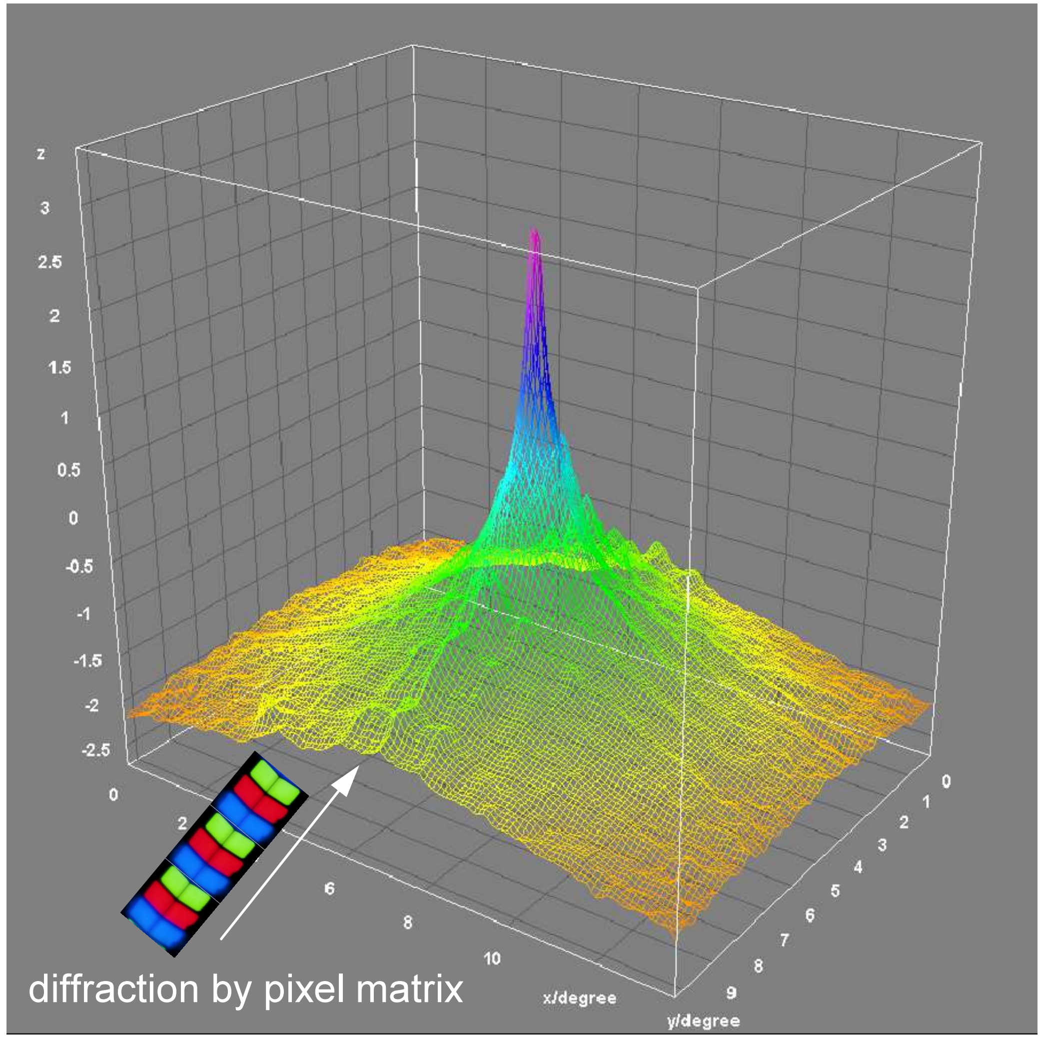


The ***mirror component*** of reflected luminance is determined by the **source luminance** in the specular direction of the LMD optical axis.

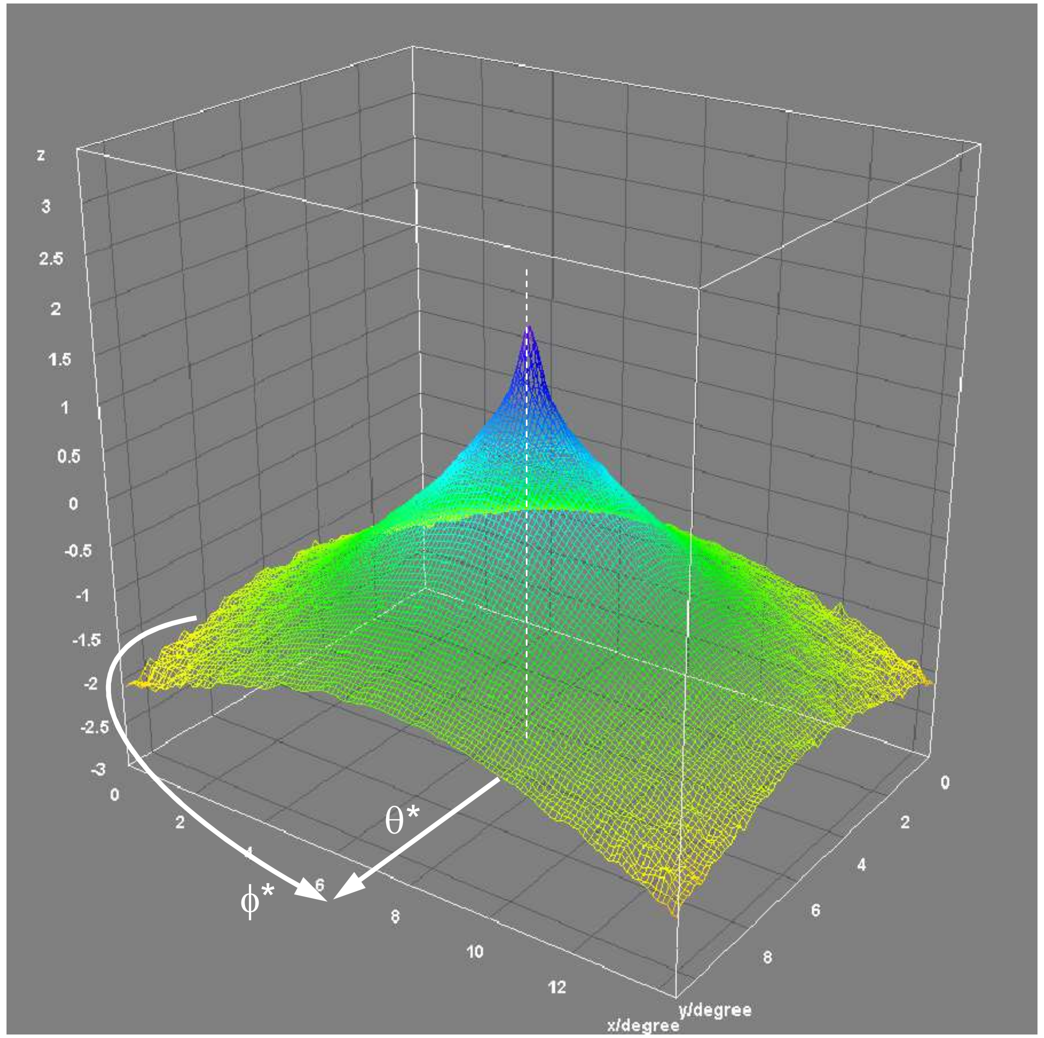
Both scattered components, ***Lambertian diffuse and haze are*** determined by the **illuminance**, their identification requires additional measurements.

A new feature has been added for measurement of the Lambertian component @ e.g. θ_i = 49° and θ_r = 4°

Reflectance analysis - computer screens



log reflected luminance [a. u.]

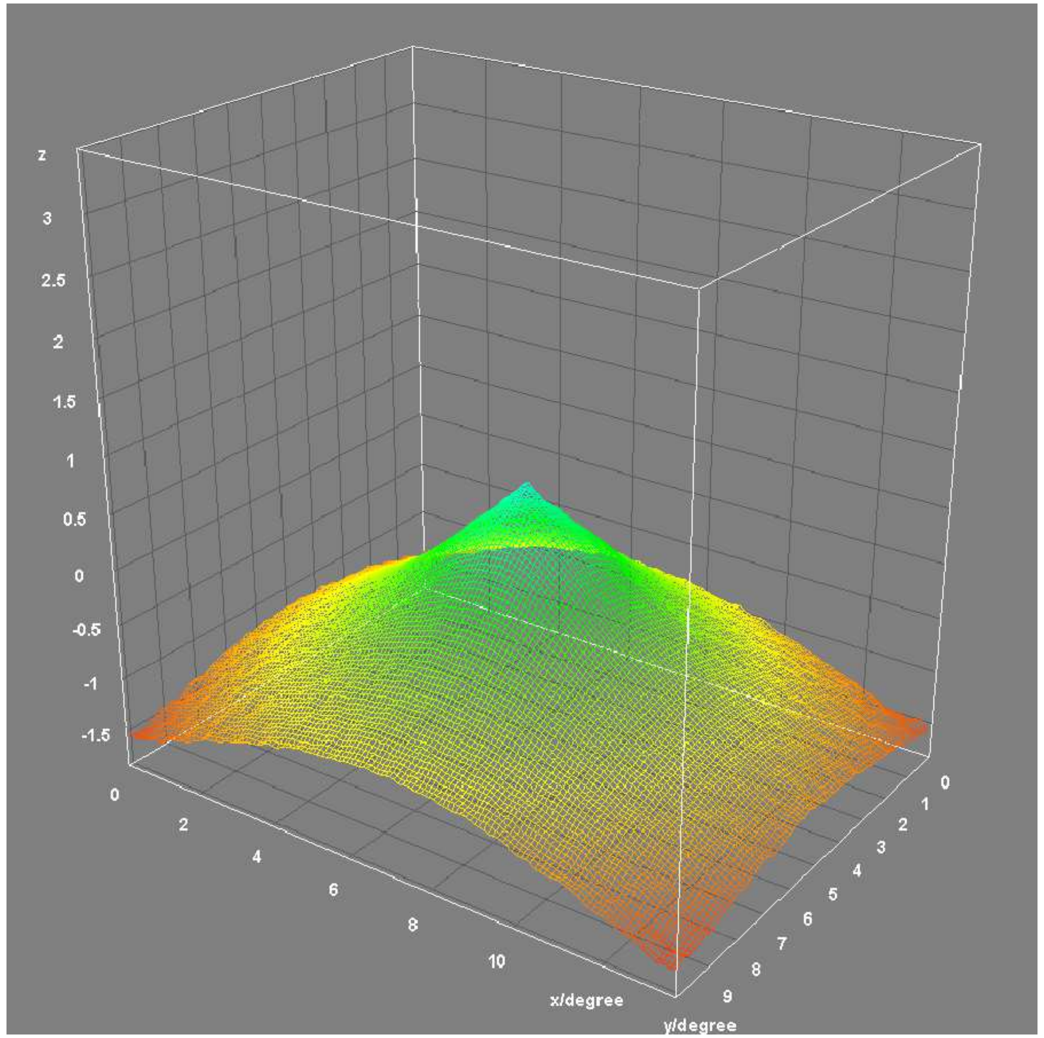


tablet screen without AG

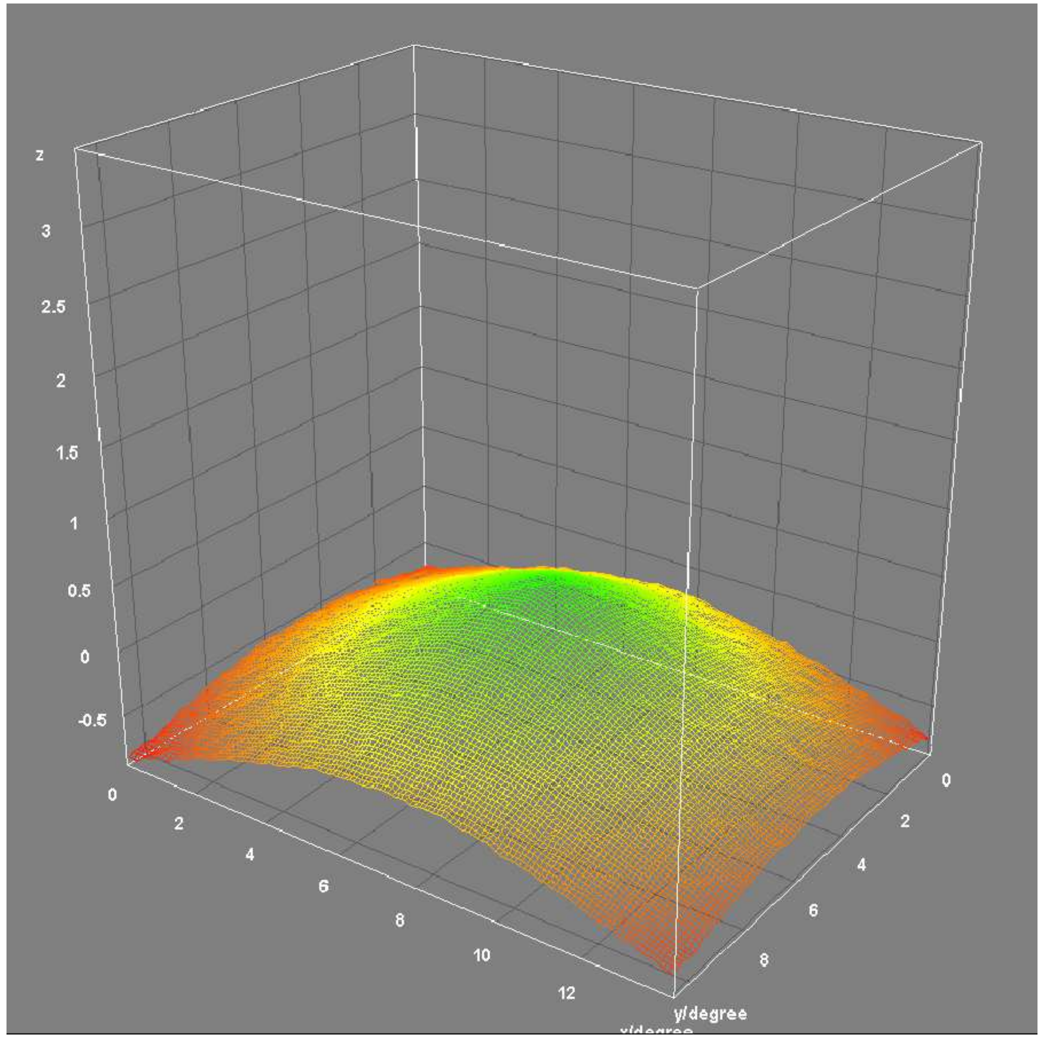
notebook screen with some AG

specification of scattering by (1) reduction in regular direction and by (2) generalized haze (i.e. off-specular / specular)

Reflectance analysis - computer screens



log reflected luminance [a. u.]

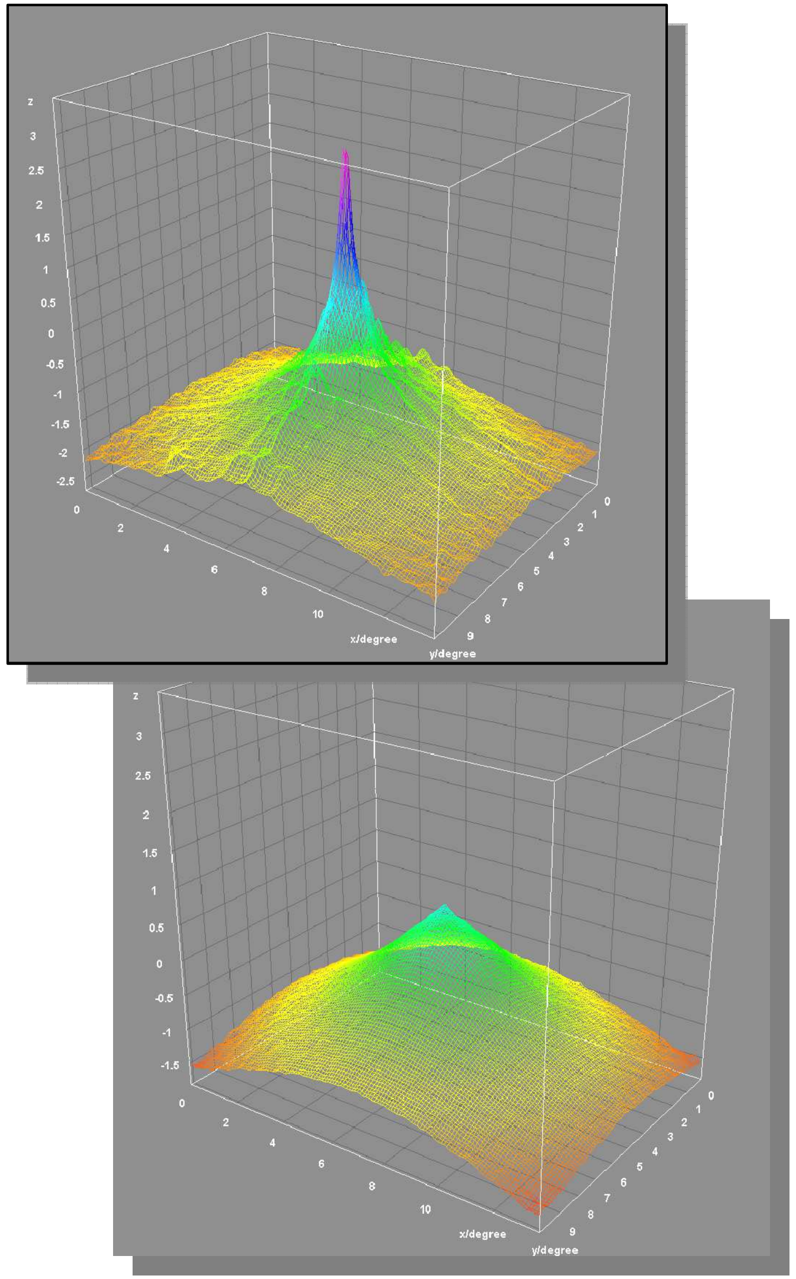


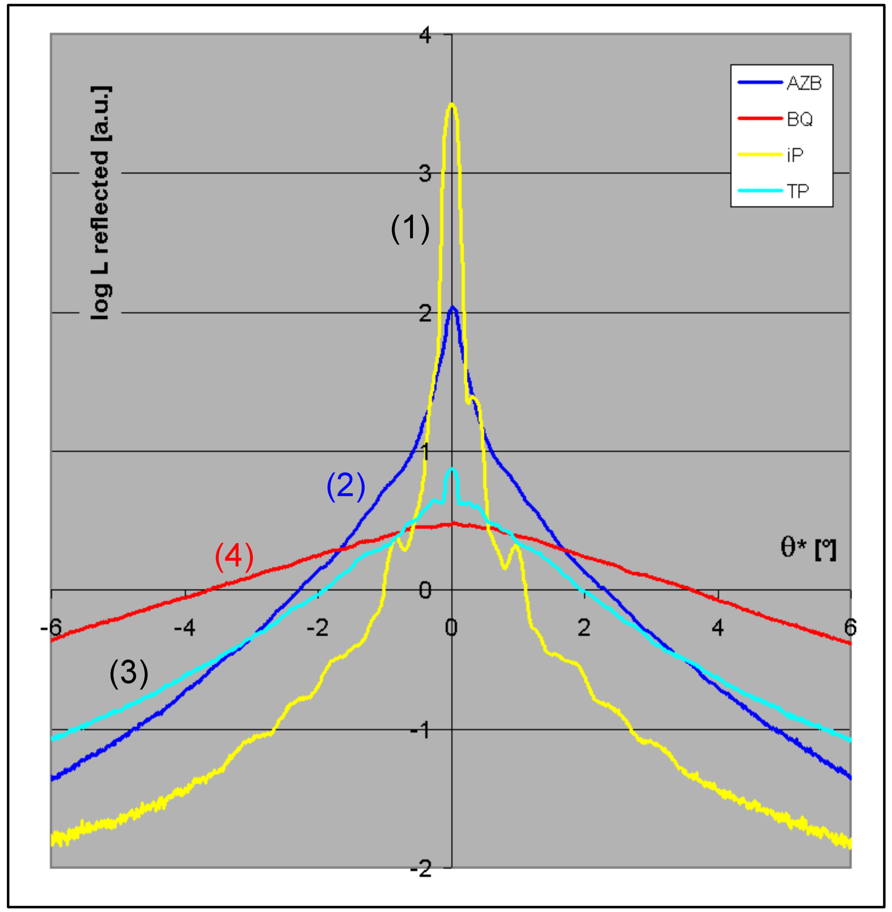
notebook screen with AG

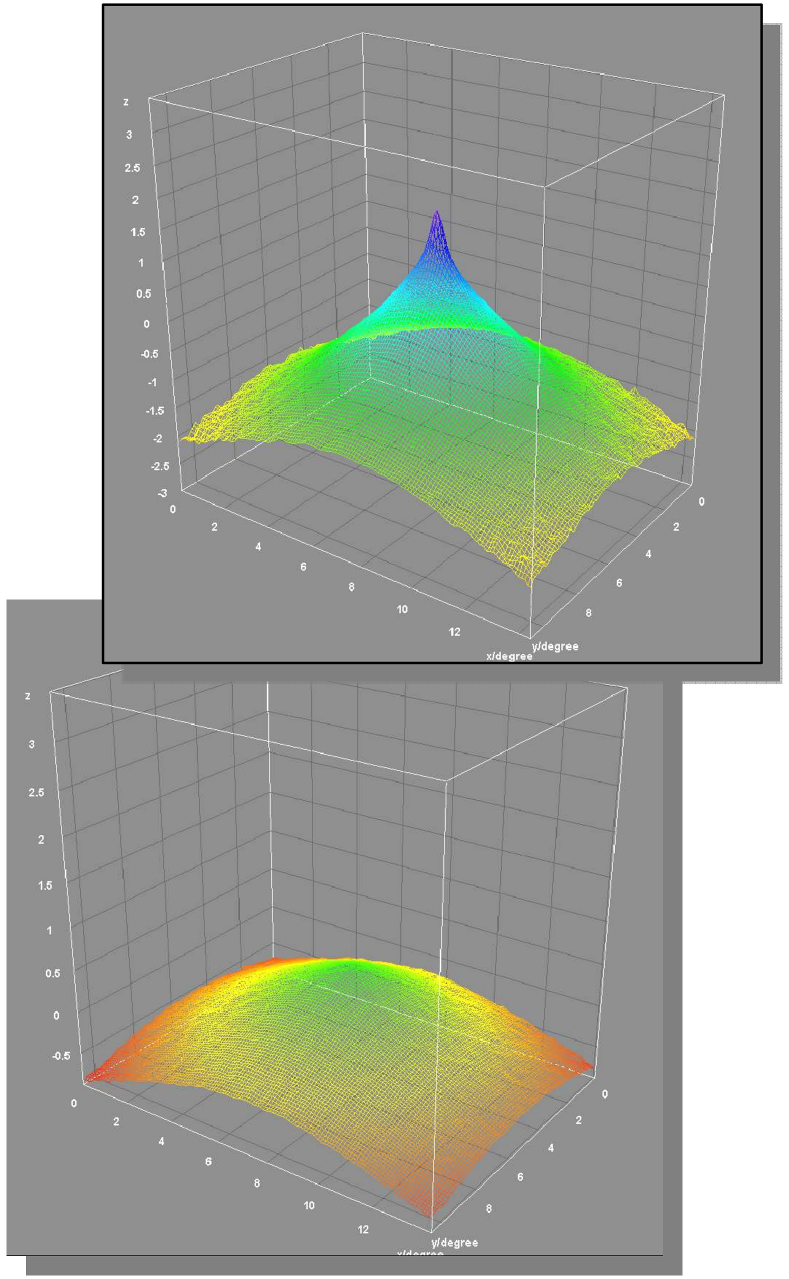
desktop screen with AG

specification of scattering by (1) reduction in regular direction and by (2) generalized haze (i.e. off-specular / specular)

Reflectance analysis - computer screens

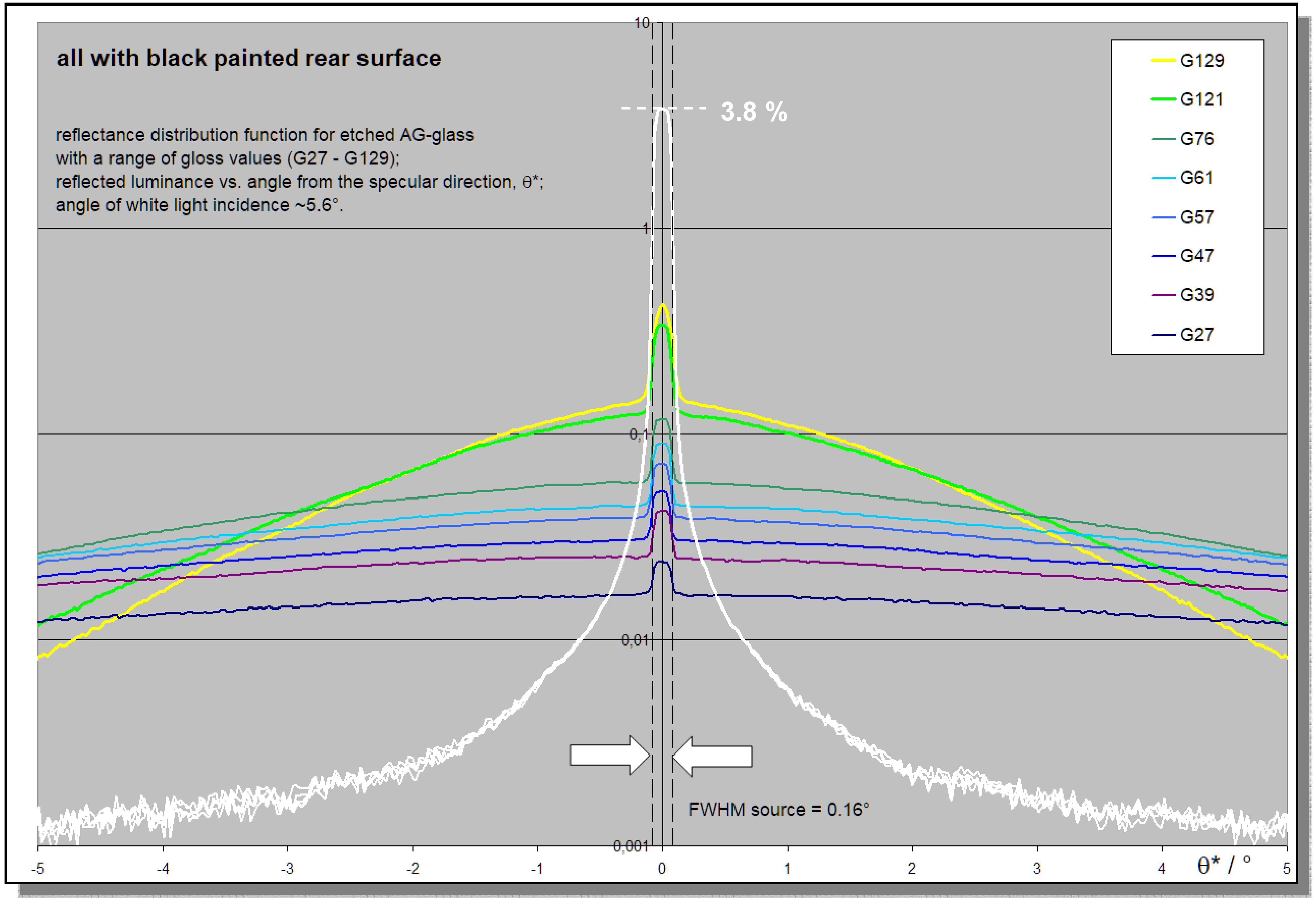




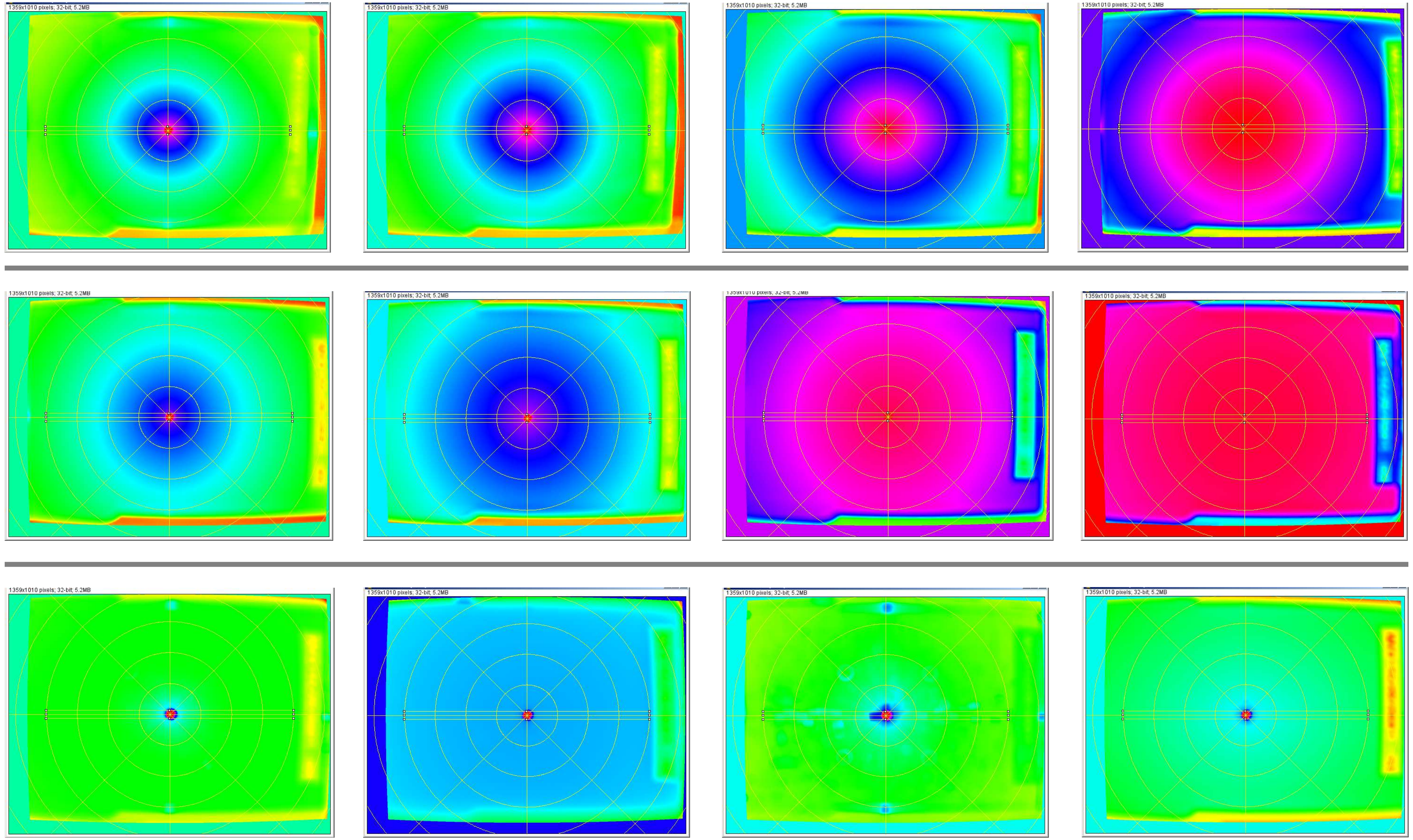


(1) mirror-image of light source with
diffraction by pixel matrix,
(2) haze with controlled specular peak,
(3) haze with small specular peak,
(4) haze without specular component.

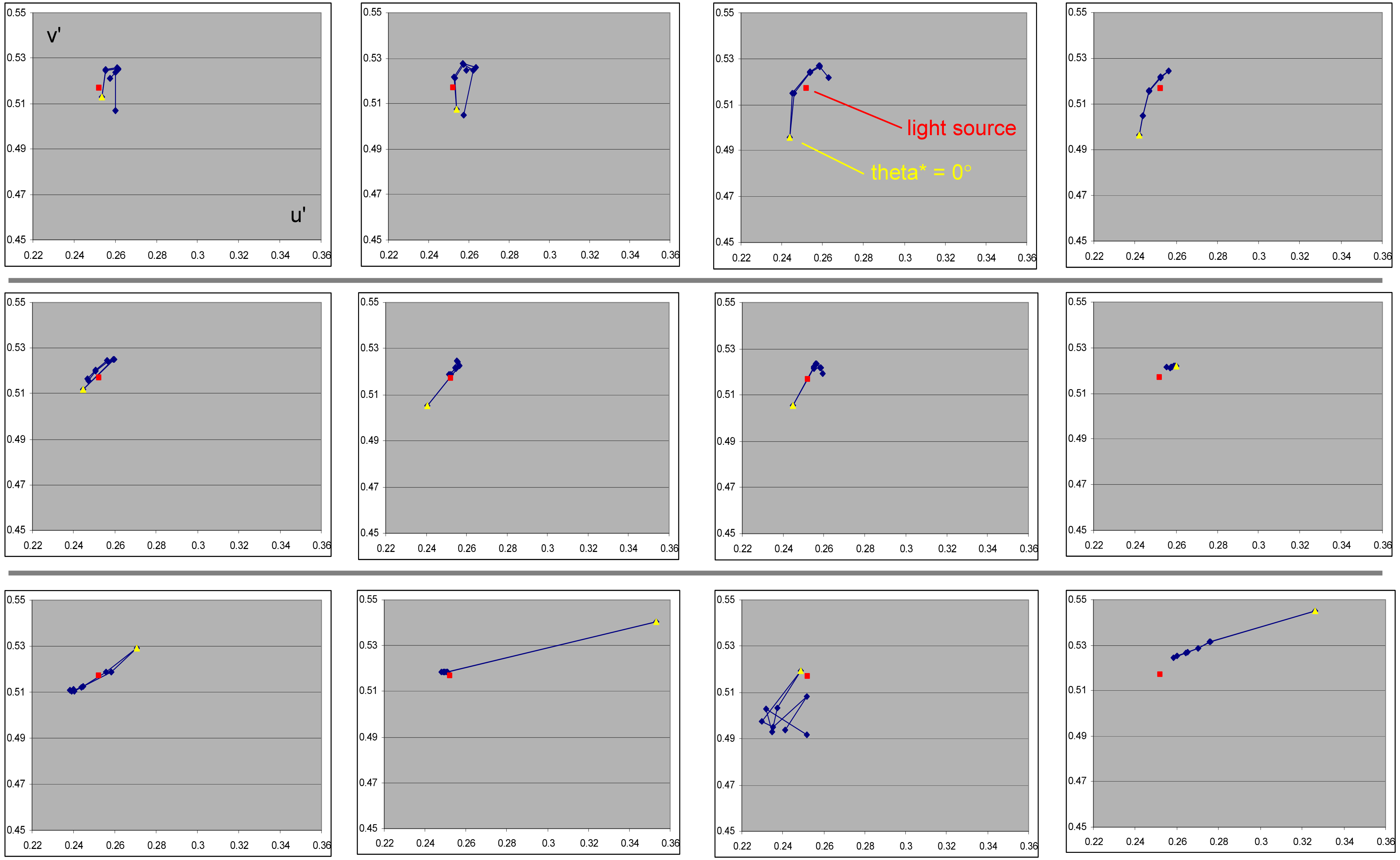
BRDF from the PSF: Characterization of AG surfaces



Translucent polymer samples with point-source illumination - luminance



Chromaticity u', v' vs. angle of inclination (horizontal plane)



Conclusions

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

- directional variations - in the vicinity of specular - are measured quickly without motorized scanning,
- adjustment and alignment of the setup are controllable by real-time images provided by the LMD,
- the peak intensity of reflected light is never missed, and
- colorimetric analysis is possible with imaging colorimeters or with tunable light sources.

The requirement for **samples with laterally uniform properties** must be fulfilled in the case of visual displays anyway, the **limitation to angles of light incidence and observation close to perpendicular** 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 that are most important for the visual experience of the observer.

The method thus provides a range of metrological benefits at a minimum of additional instrumental efforts. It offers access to separation of disturbing reflections from those that forward visual information as a basis for optimization of the visual performance of electronic displays.

Conclusions

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

- directional variations are measured quickly without motorized scanning,
- adjustment and alignment of the setup are controllable by real-time images provided by the LMD,
- the peak intensity of reflected light is never missed, and
- colorimetric analysis is possible with imaging colorimeters or with tunable light sources.

The requirement for **samples with laterally uniform properties** must be fulfilled in the case of visual displays anyway, the **limitation to angles of light incidence and observation close to perpendicular** 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 that are most important for the visual experience of the observer.

The method thus provides a range of metrological benefits at a minimum of additional instrumental efforts. It offers access to separation of disturbing reflections from those that forward visual information as a basis for optimization of the visual performance of electronic displays.

Conclusions

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

- directional variations are measured quickly without motorized scanning,
- adjustment and alignment of the setup are controllable by real-time images provided by the LMD,
- the peak intensity of reflected light is never missed, and
- colorimetric analysis is possible with imaging colorimeters or with tunable light sources.

The requirement for **samples with laterally uniform properties** must be fulfilled in the case of visual displays anyway, the **limitation to angles of light incidence and observation close to perpendicular** 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 that are most important for the visual experience of the observer.

The method provides a range of metrological benefits at a minimum of instrumental efforts.
It offers access to separation of disturbing reflections from those that forward visual information as a basis for optimization of the visual performance of electronic displays.

Thank you for your attention !