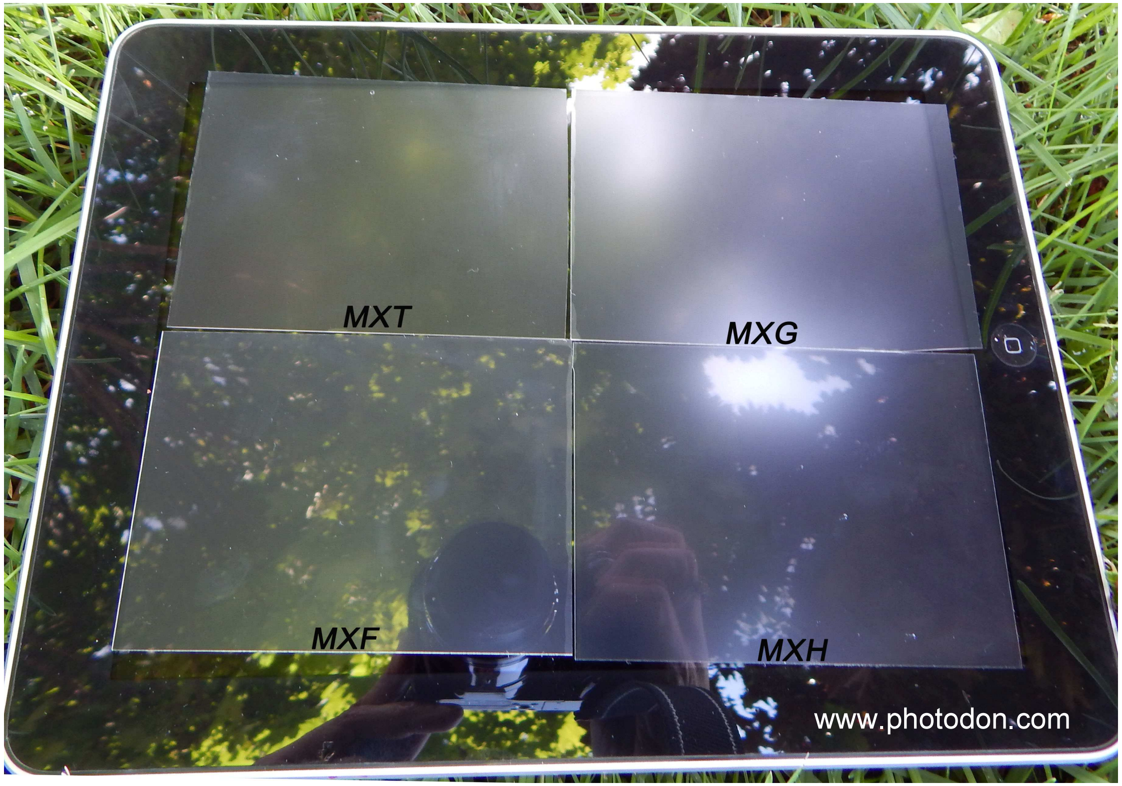
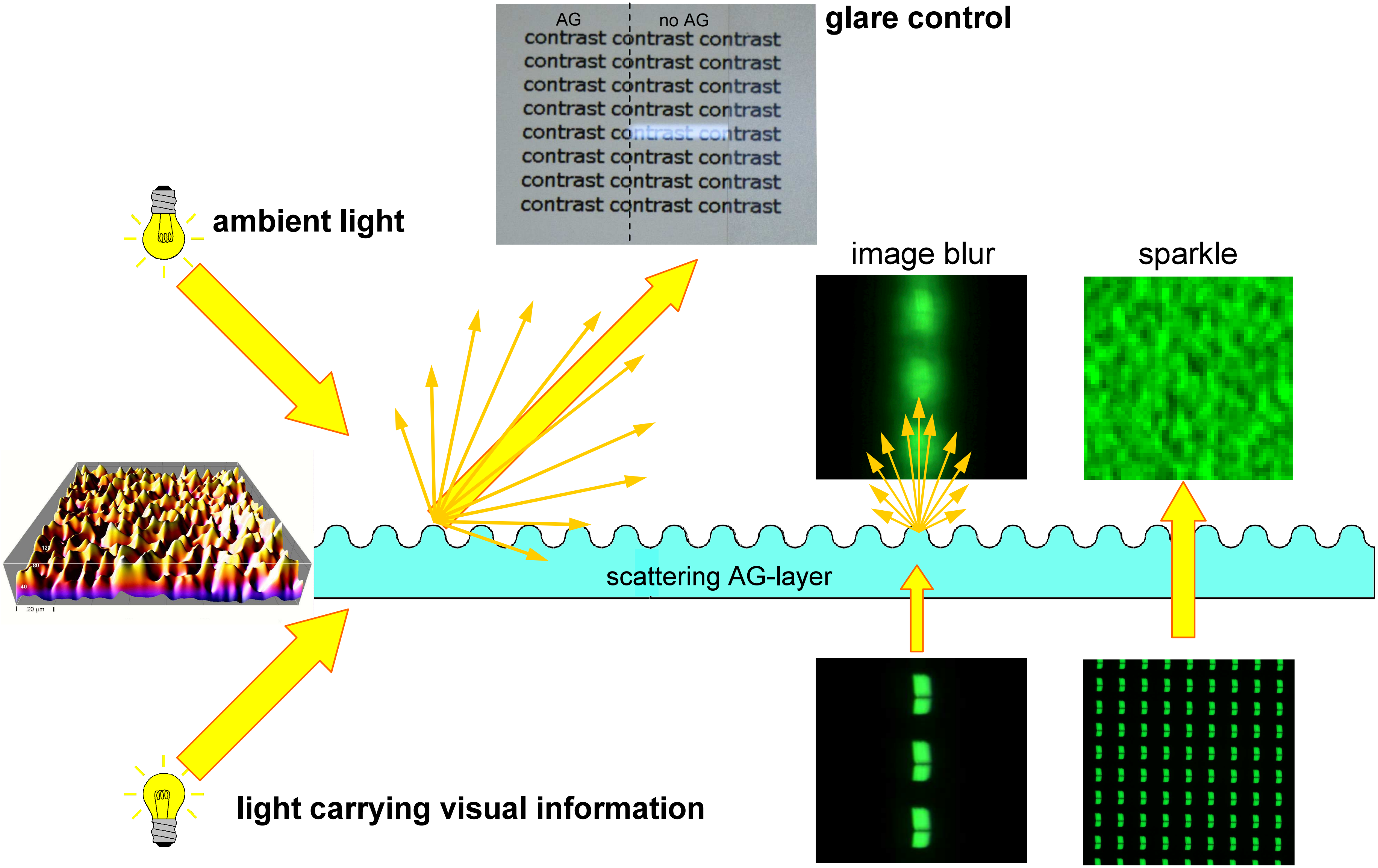
Optimization of Display-Systems

with respect to **Glare**, **Distinctness of Image** and **Sparkle**

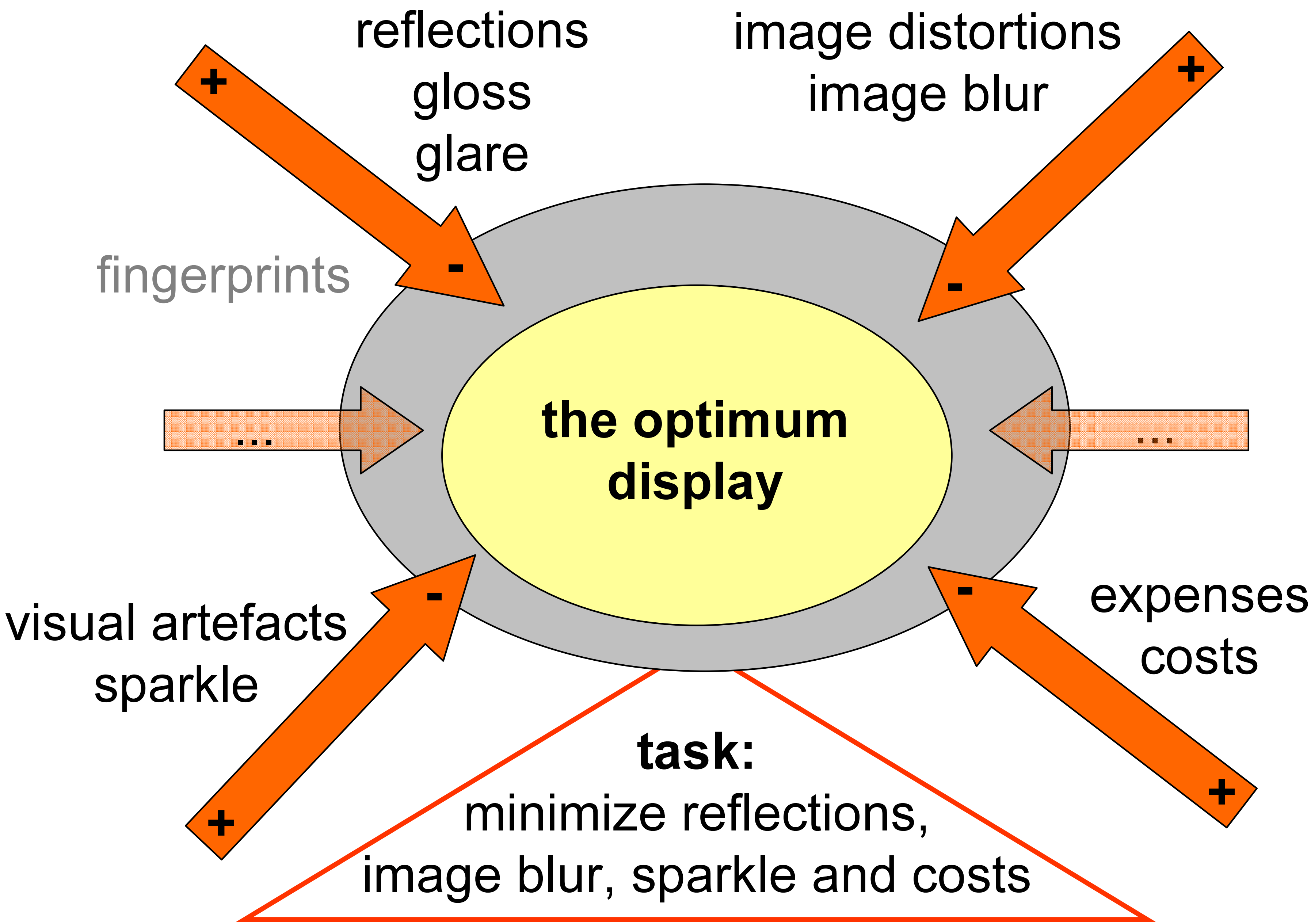


Michael E. Becker – Display-Messtechnik&Systeme - Rottenburg am Neckar

Optimization of Displays with an AG-Layer

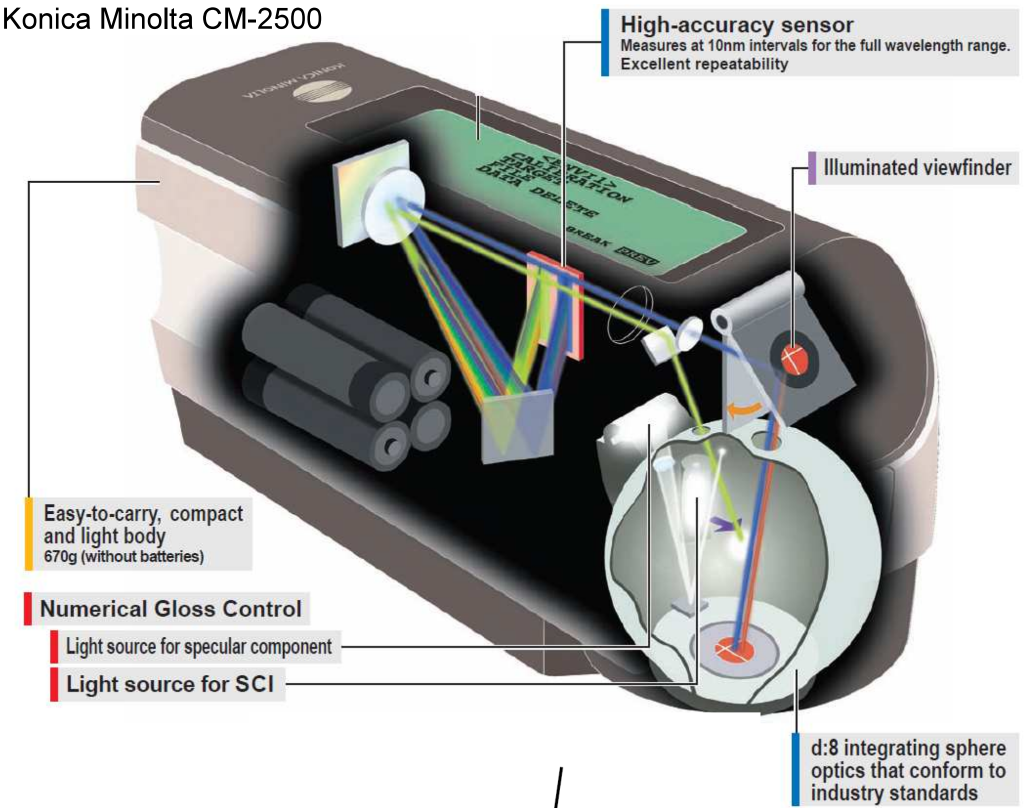


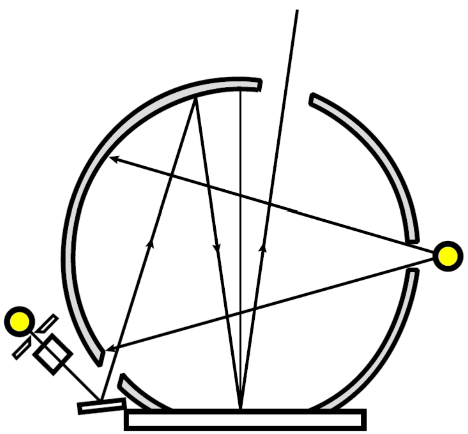
Optimization Task

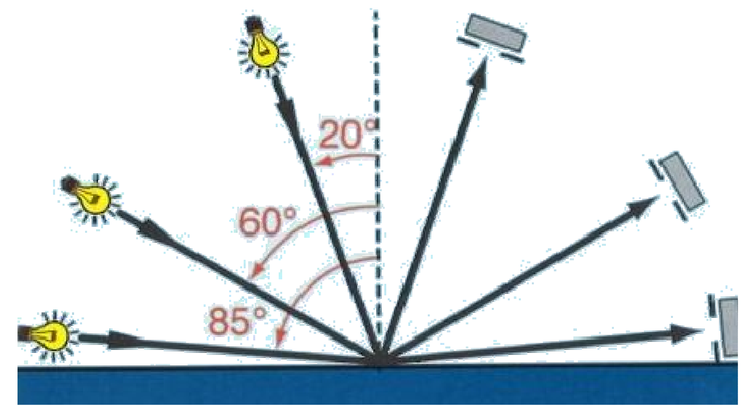


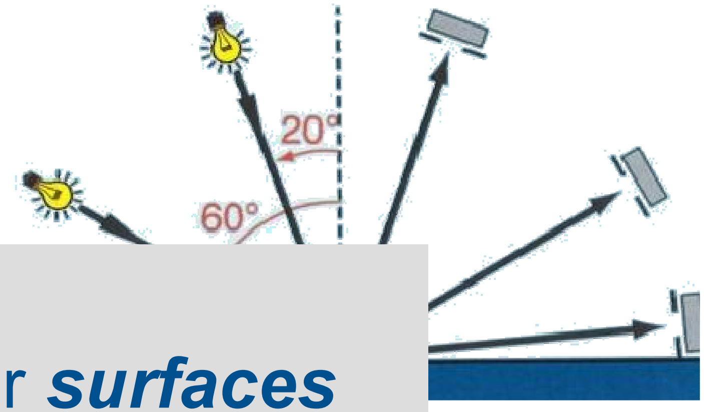
Characterization of Reflectance

Konica Minolta CM-2500



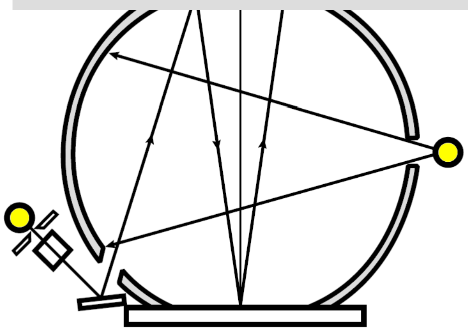




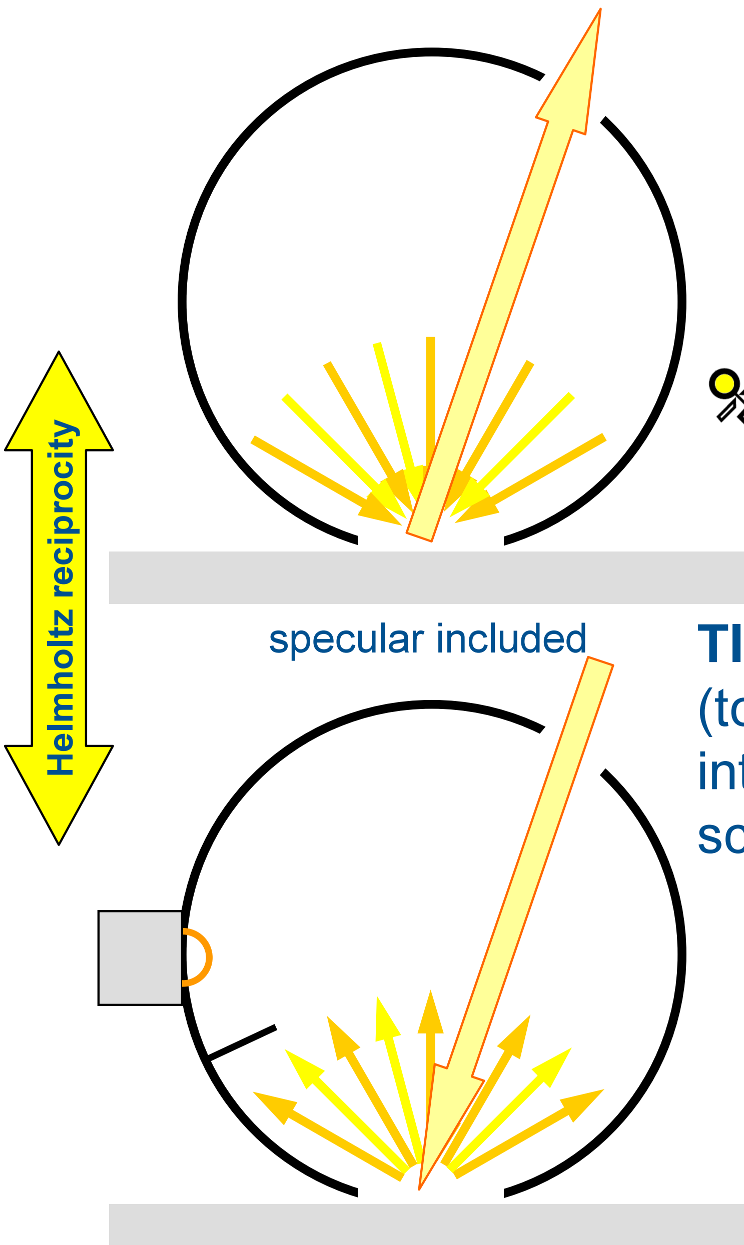


Both devices are made for ***surfaces*** covered with paint, pigments, etc.

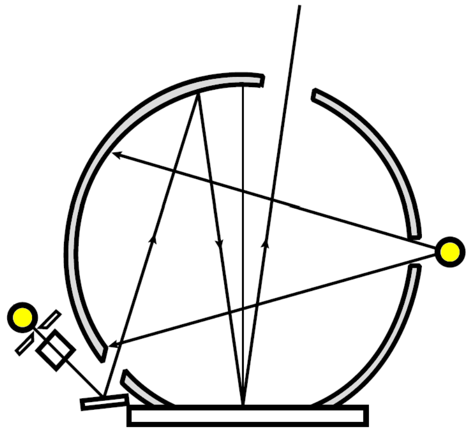
They are NOT suited for characterization of transparent samples.



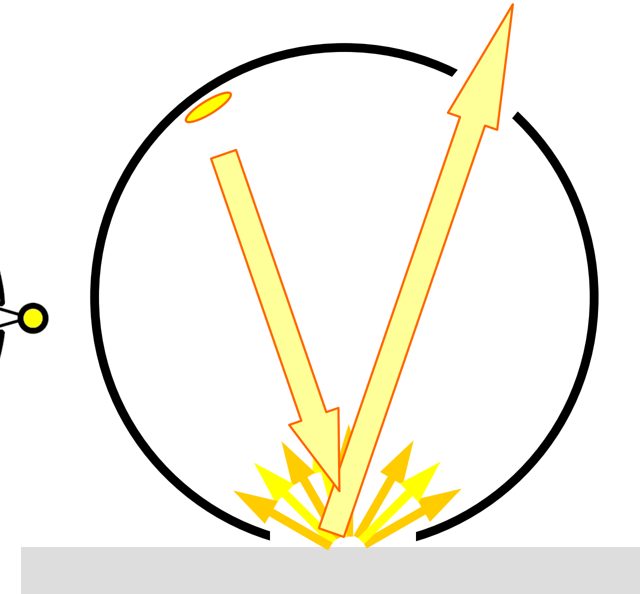
Characterization of Reflectance



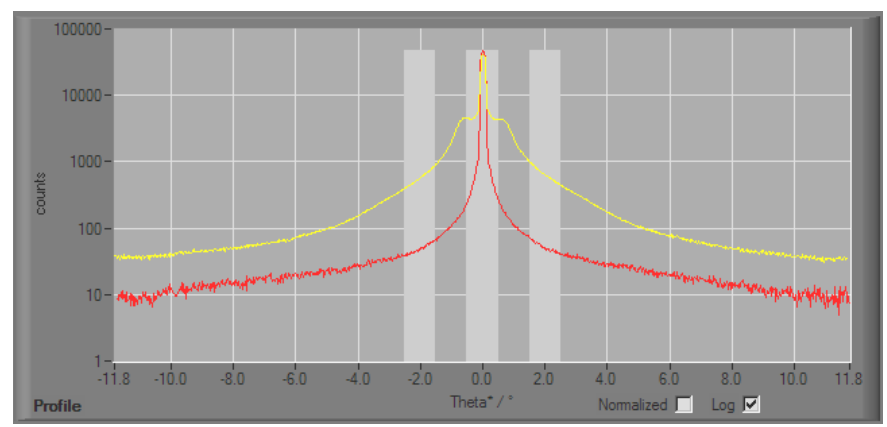
specular included



TIS
(total integrated scatter)

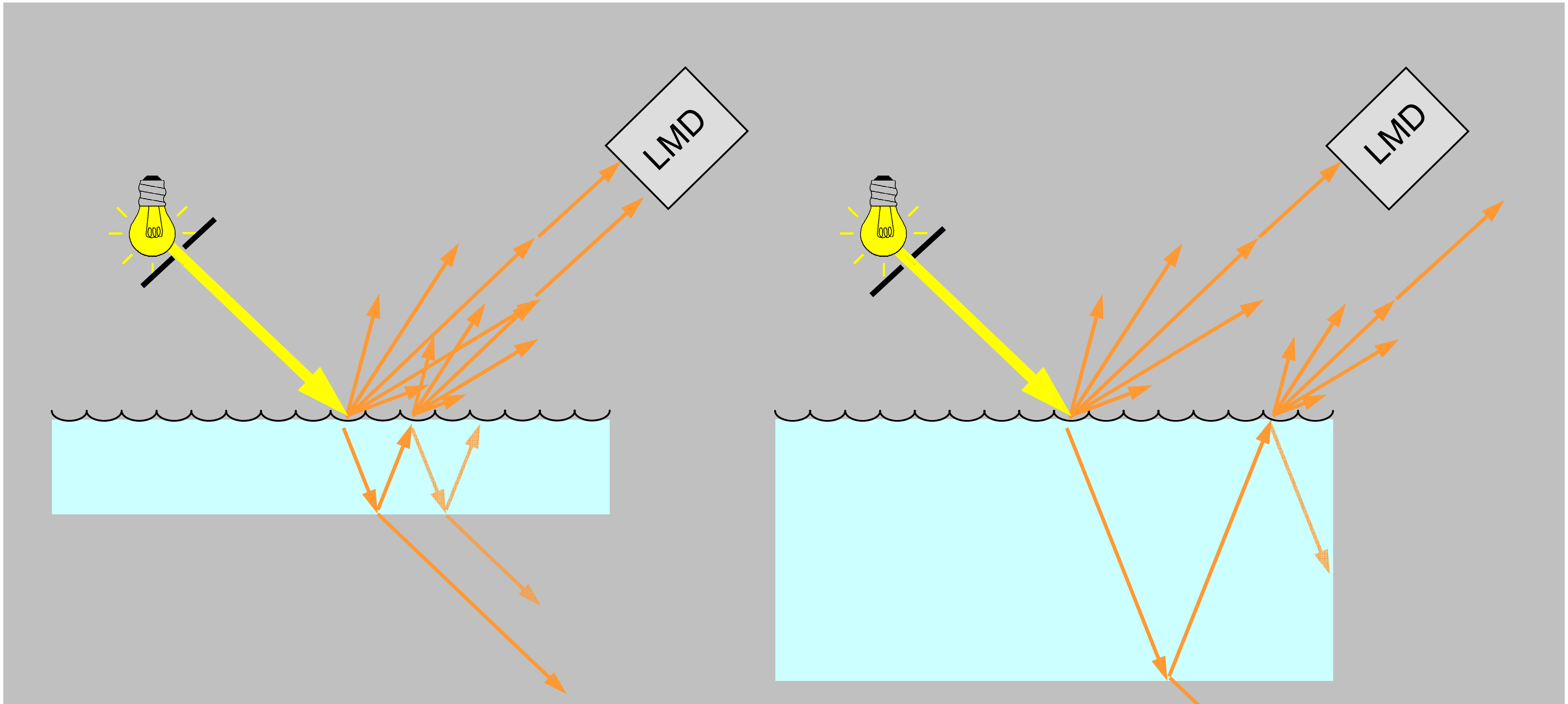


specular only



high-resolution reflectance distribution function

with a gloss-meter



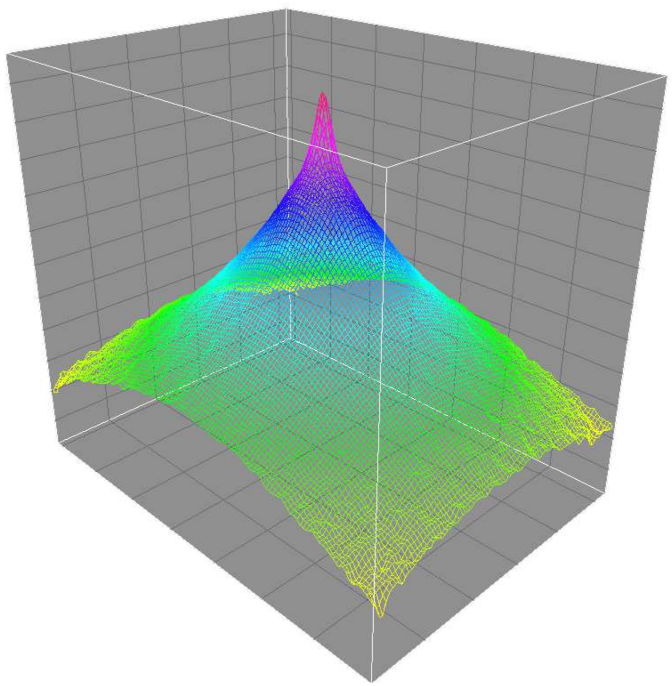
Gloss-Meter reading 1

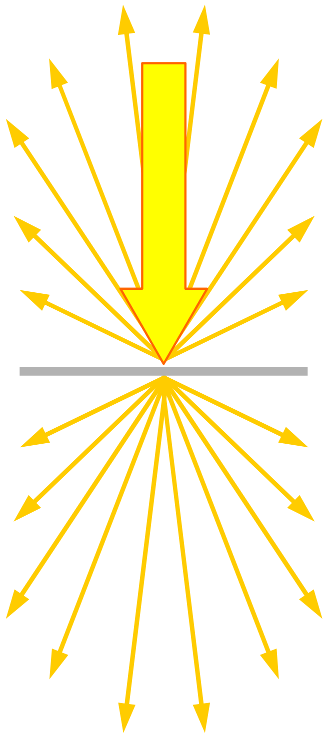
Gloss-Meter reading 2<1

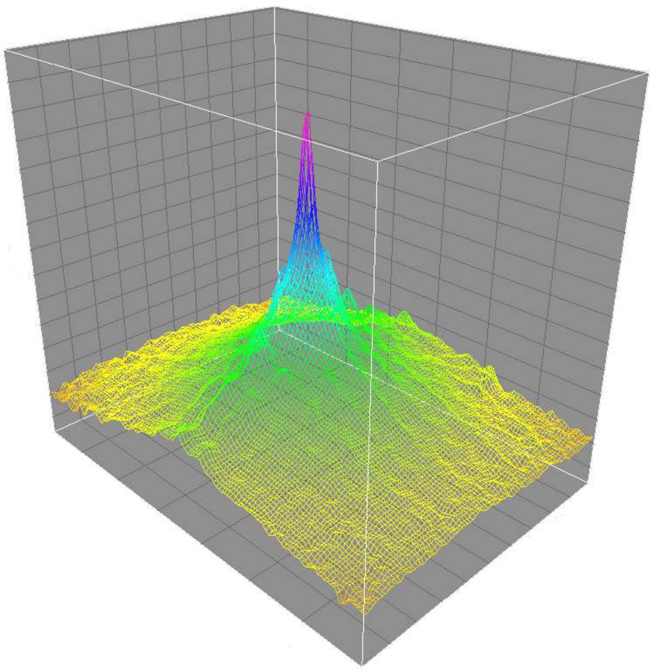
Gloss level of 100% given by specular reflection from a ***polished black glass surface*** (n = 1,567 @ 589 nm).

Increasing gloss level ➔ decreasing scattering (at same substrate thickness!)

High-Resolution Scatter Analysis of Anti-Glare Layer Reflection



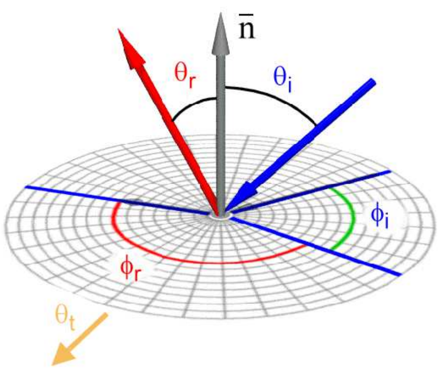




Proc. SID 2016

Directional Scanning

$$dL_s(\theta_s,\phi_s) = B(\theta_i,\phi_i,\theta_s,\phi_s;\lambda,\vec{p}) \quad dE(\theta_i,\phi_i)$$



The scattering properties of surfaces are generally and completely described by the *bidirectional scatter distribution function* (BSDF) which is a function of the direction of light incidence, the direction of observation, the wavelength of light and its state of polarization.

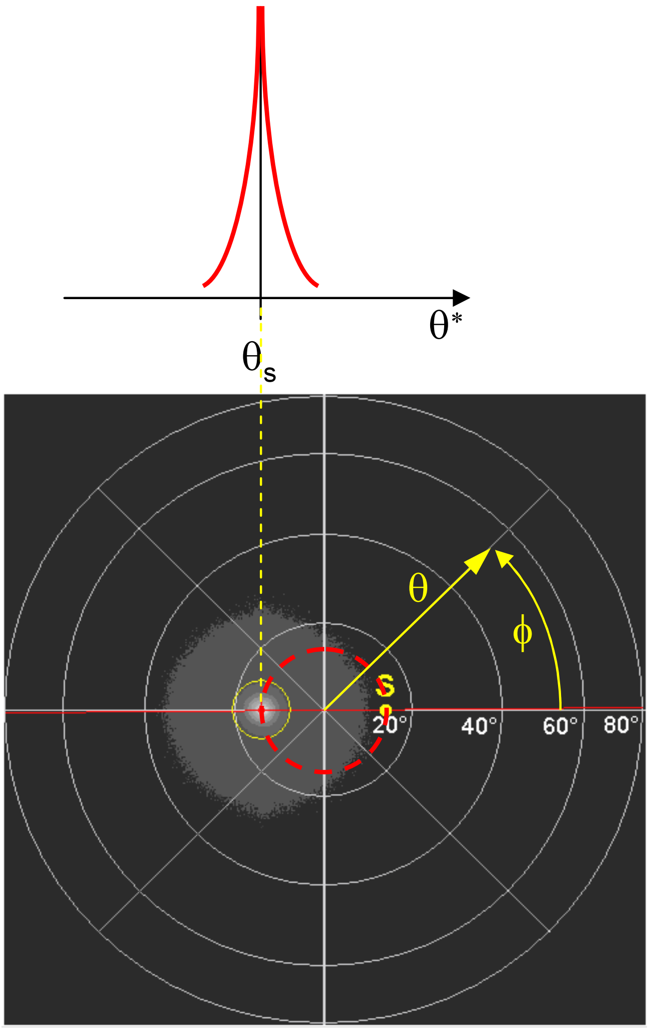
Assessment and evaluation of the reflective properties of surfaces can be realized by

- **mechanical** (**motorized) scanning of a range of observation directions** with photometric or spectro-radiometric receivers for one direction of light incidence. This can be done with complex, and bulky high-precision mechanisms (gonio-photometer or gonio-spectroradiometer).

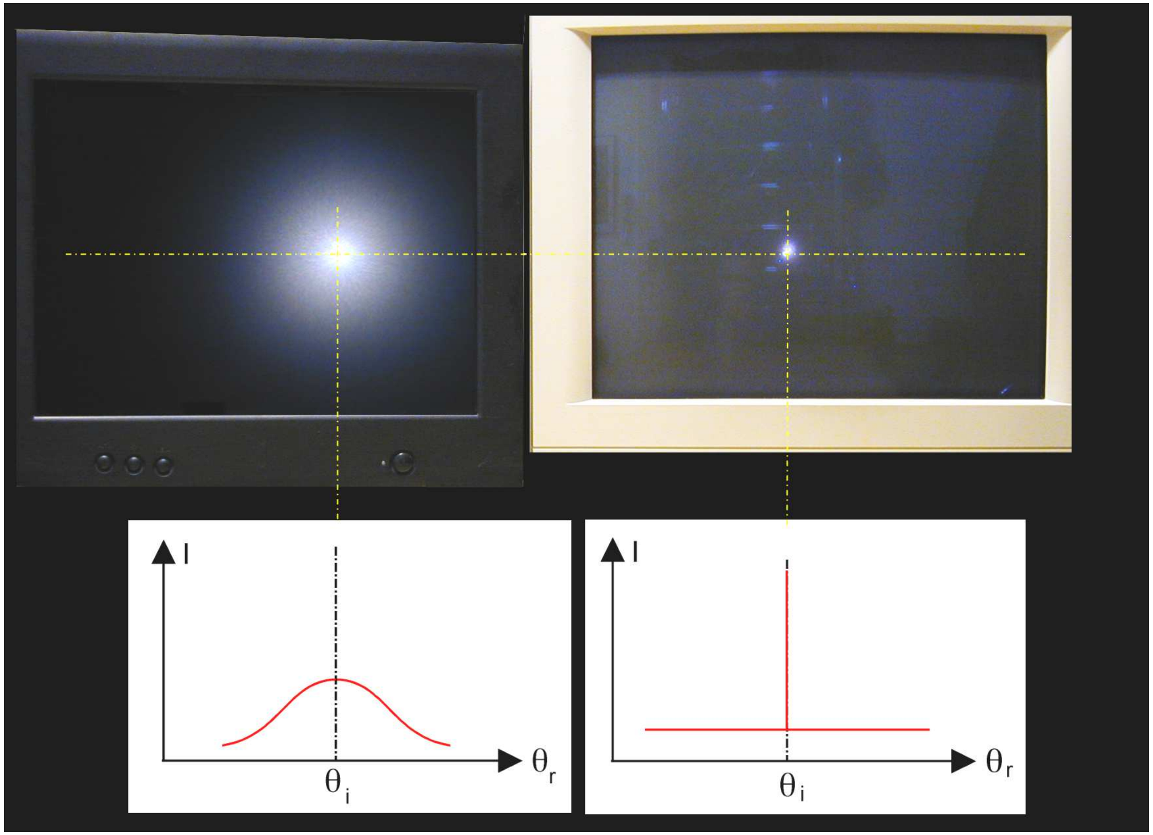
Scanning of the directions of observation **without moving parts**:

- **optical scanning (conoscopy),**
- analysis of the spreading of a point- or line-source of illumination (**PSF - LSF approach**),
- hemispherical projection and imaging ("**imaging hemisphere**").

Conoscopic approach
collimated beam illumination



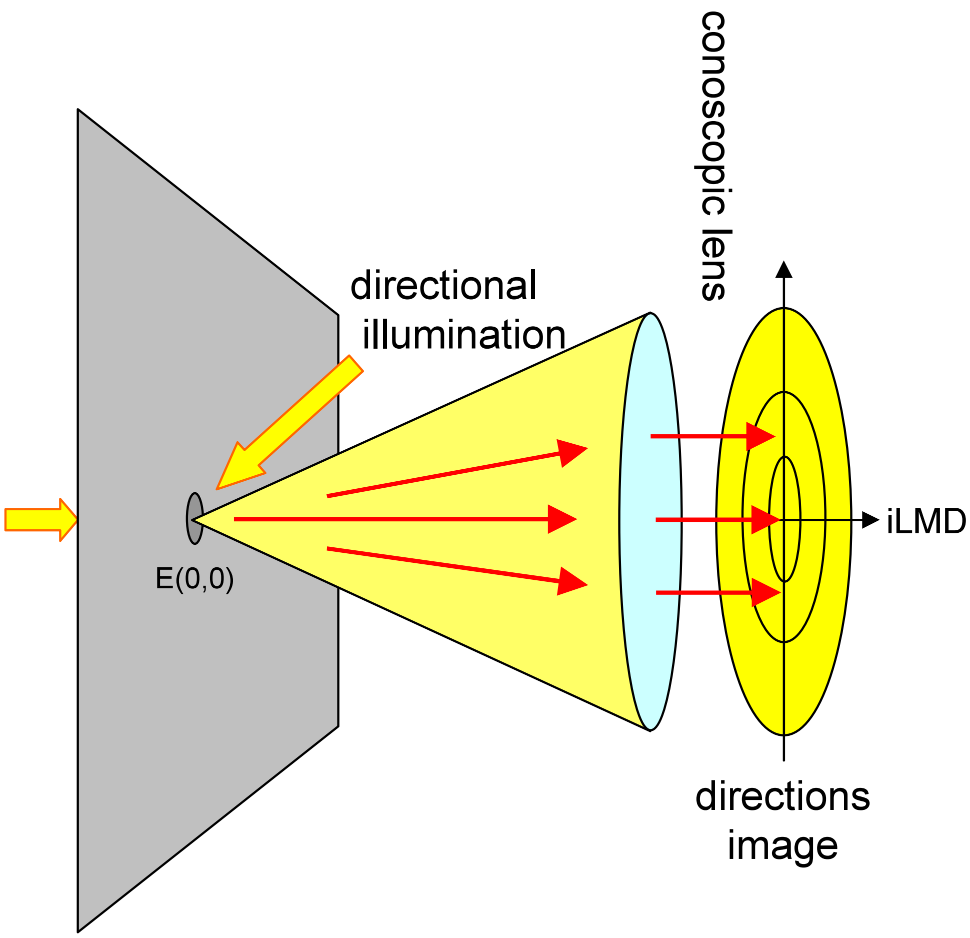
Imaging approach
point-source illumination



Basic components of reflection obvious in PSF-image:

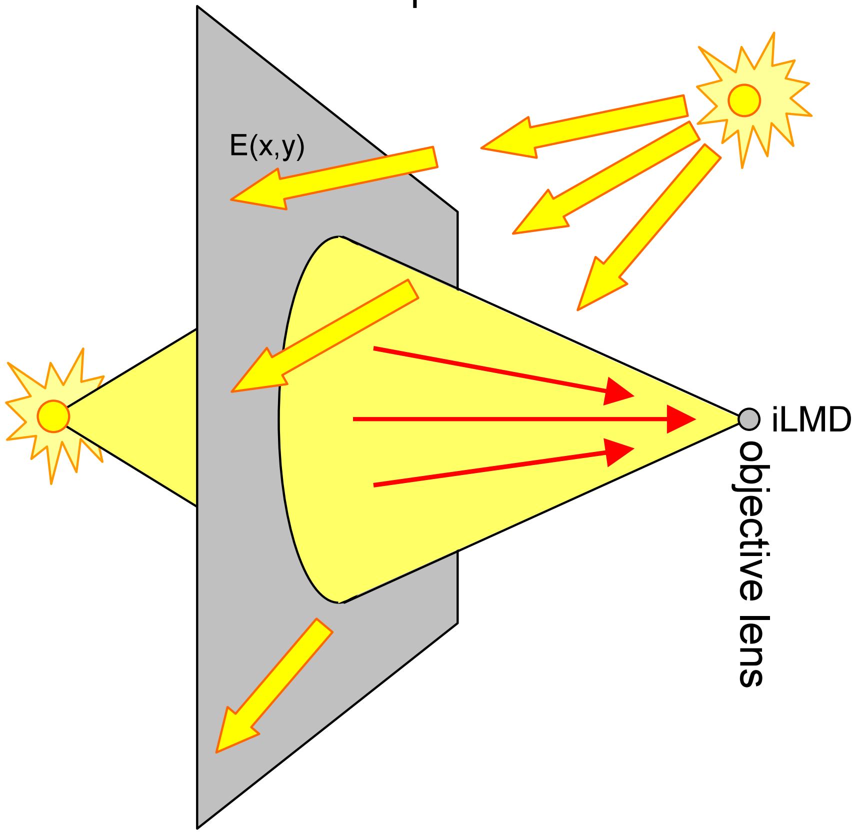
- **specular peak (width of the source)**
- **haze ("fuzzy ball" in image, bell shaped profile)**
- **Lambertian (constant plateau)**

Conoscopic approach



directional analysis of light from
one area element

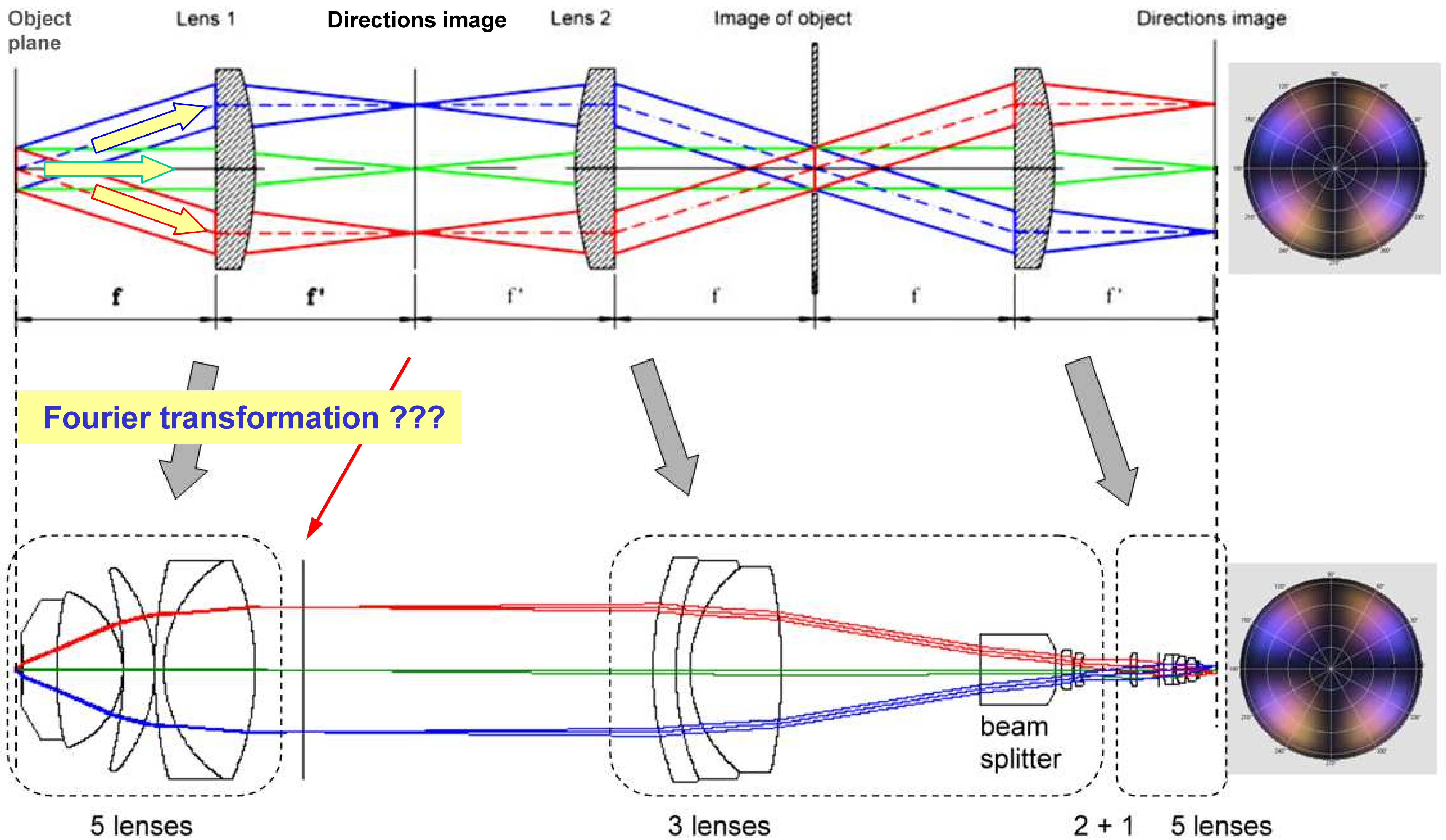
Imaging approach



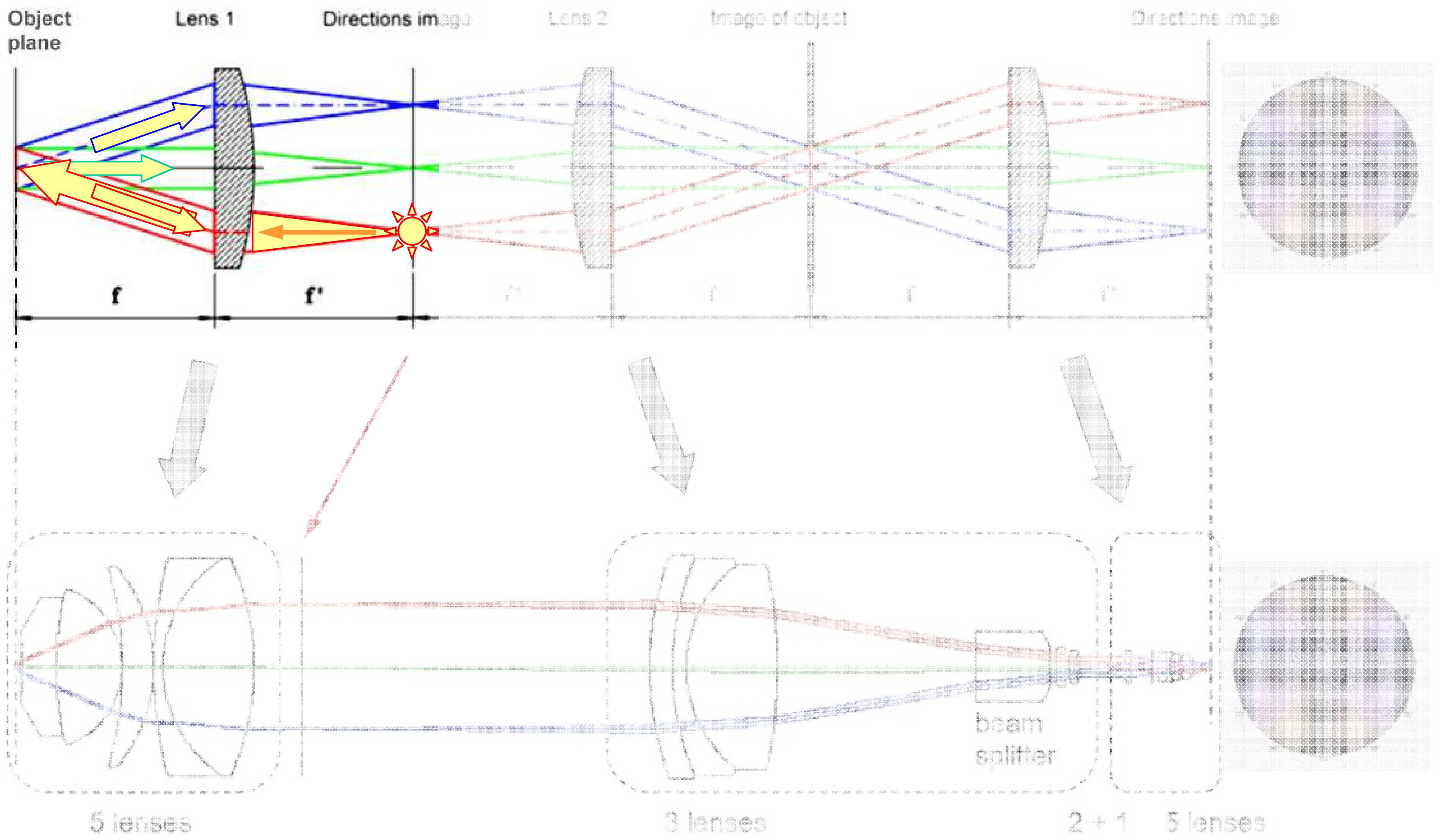
directional analysis of light from
an extended area

! properties must be uniform !

Conoscopic imaging system

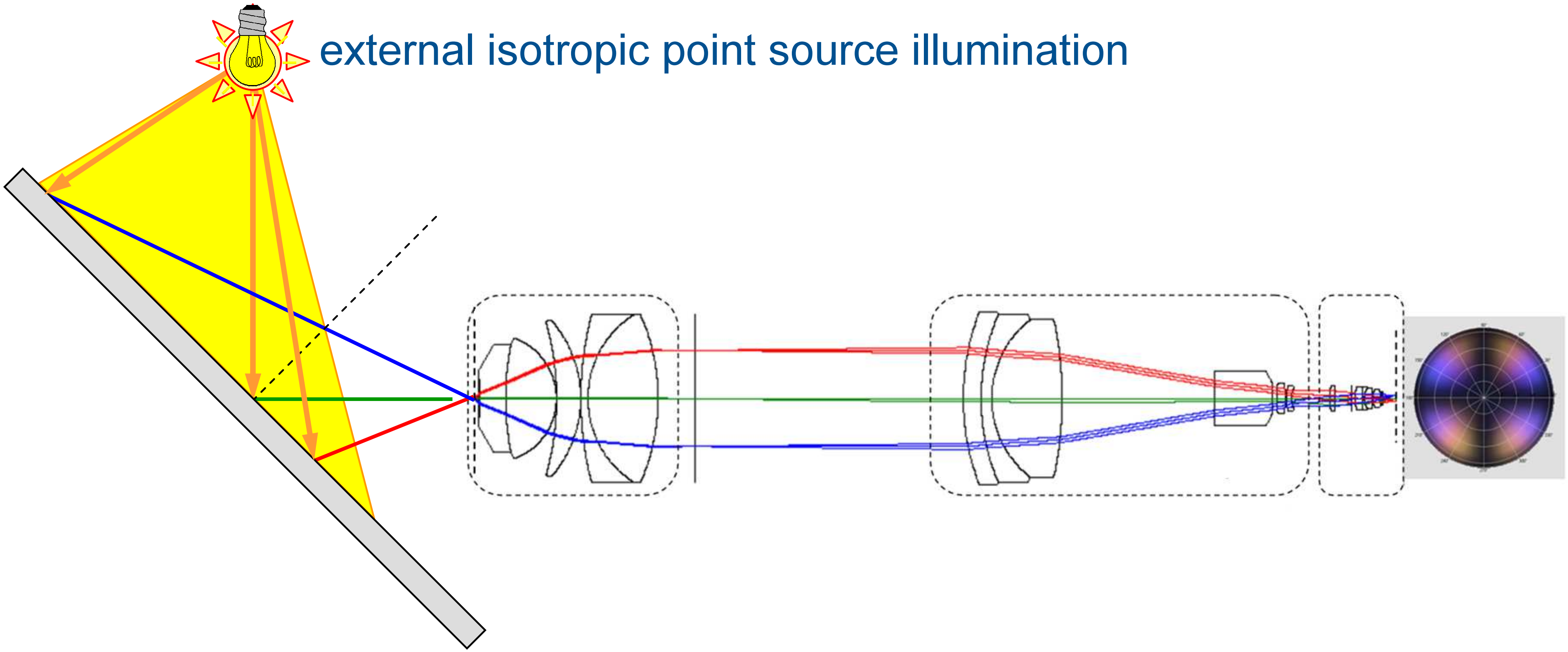


Conoscopic imaging system - reflective illumination 1



Conoscopic imaging system - reflective illumination 2

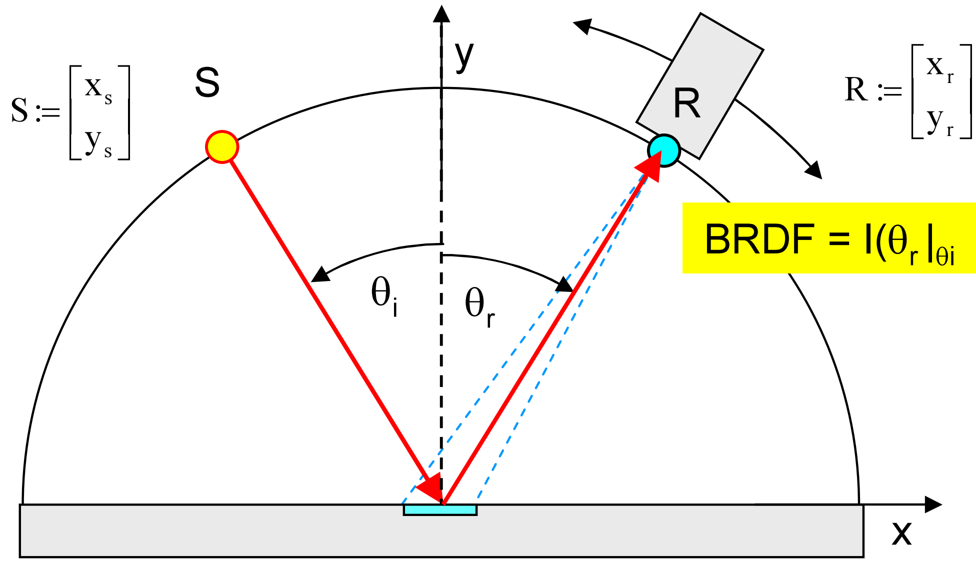
external isotropic point source illumination



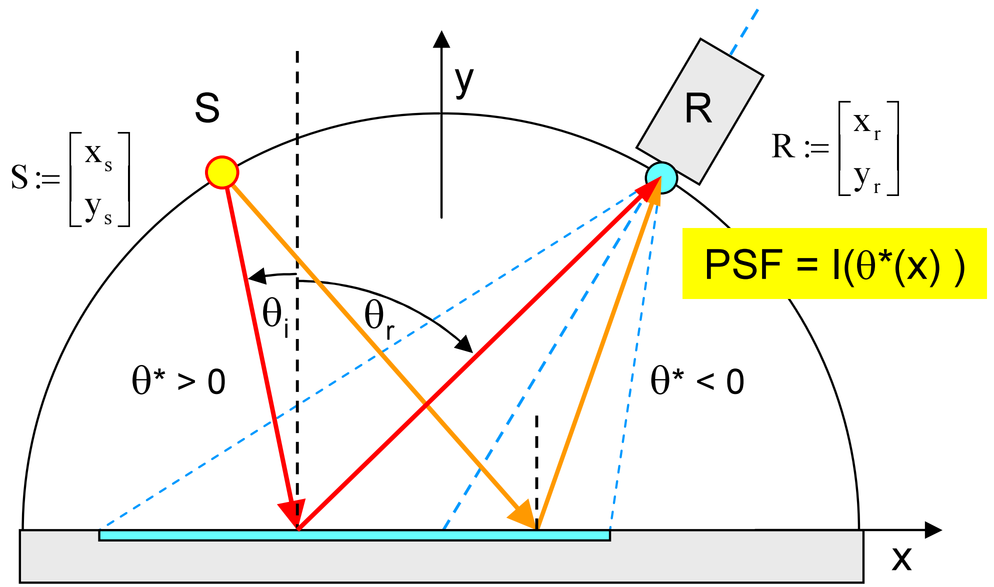
Conoscopic lens system used as fisheye lens

PSF - LSF Analyis vs. Directional Scanning

Method 1



Method 2



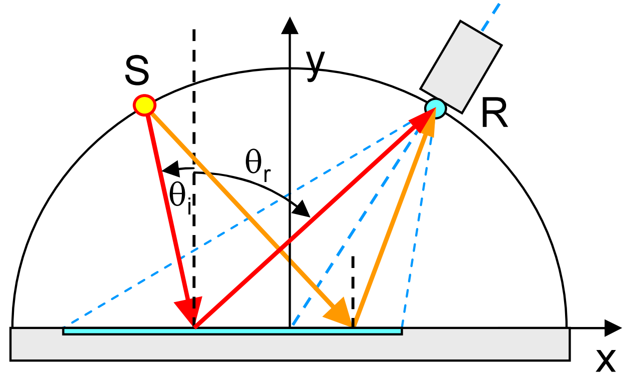
$$\theta_i(x) = \arctan\left(\frac{x - x_s}{y_s}\right) \qquad \theta_r(x) = \arctan\left(\frac{x - x_r}{y_r}\right)$$

PSF - LSF Analyis vs. Directional Scanning

$$R_p = \left| \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \right|^2$$

$$R_s = \left| \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right|^2$$

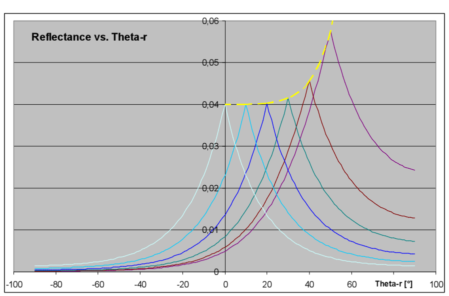
$$R = \frac{R_s + R_p}{2}$$

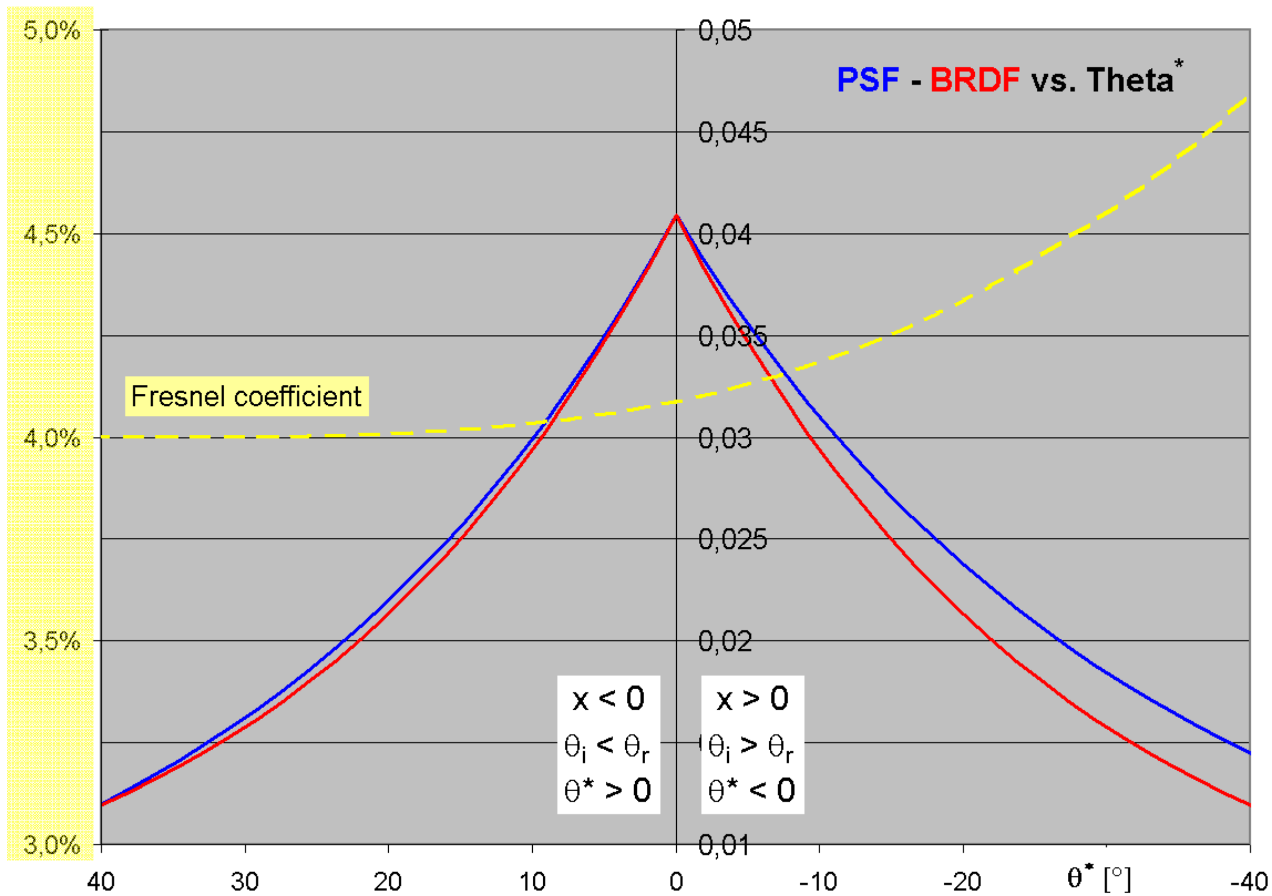


x_s = -50 mm, y_s = 100 mm
x_r = 50 mm, y_r = 100 mm

θ_i (x = 0) = 26,56°

$$\mathrm{BRDF} = \mathrm{R}(\theta_i) \cdot \exp\left(\left| \frac{\sin\theta_r - \sin\theta_i}{\mathrm{w}} \right| \right)$$



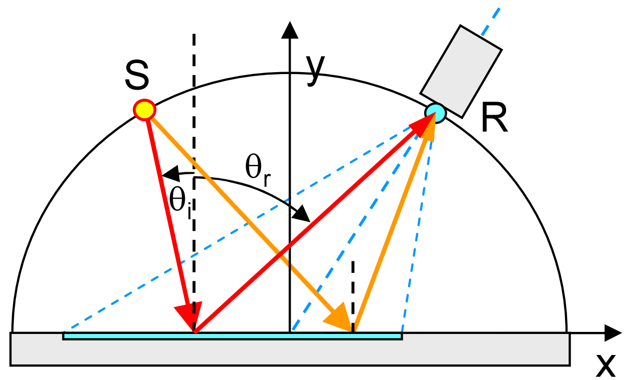


PSF - LSF Analyis vs. Directional Scanning

$$R_p = \left| \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} \right|^2$$

$$R_s = \left| \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right|^2$$

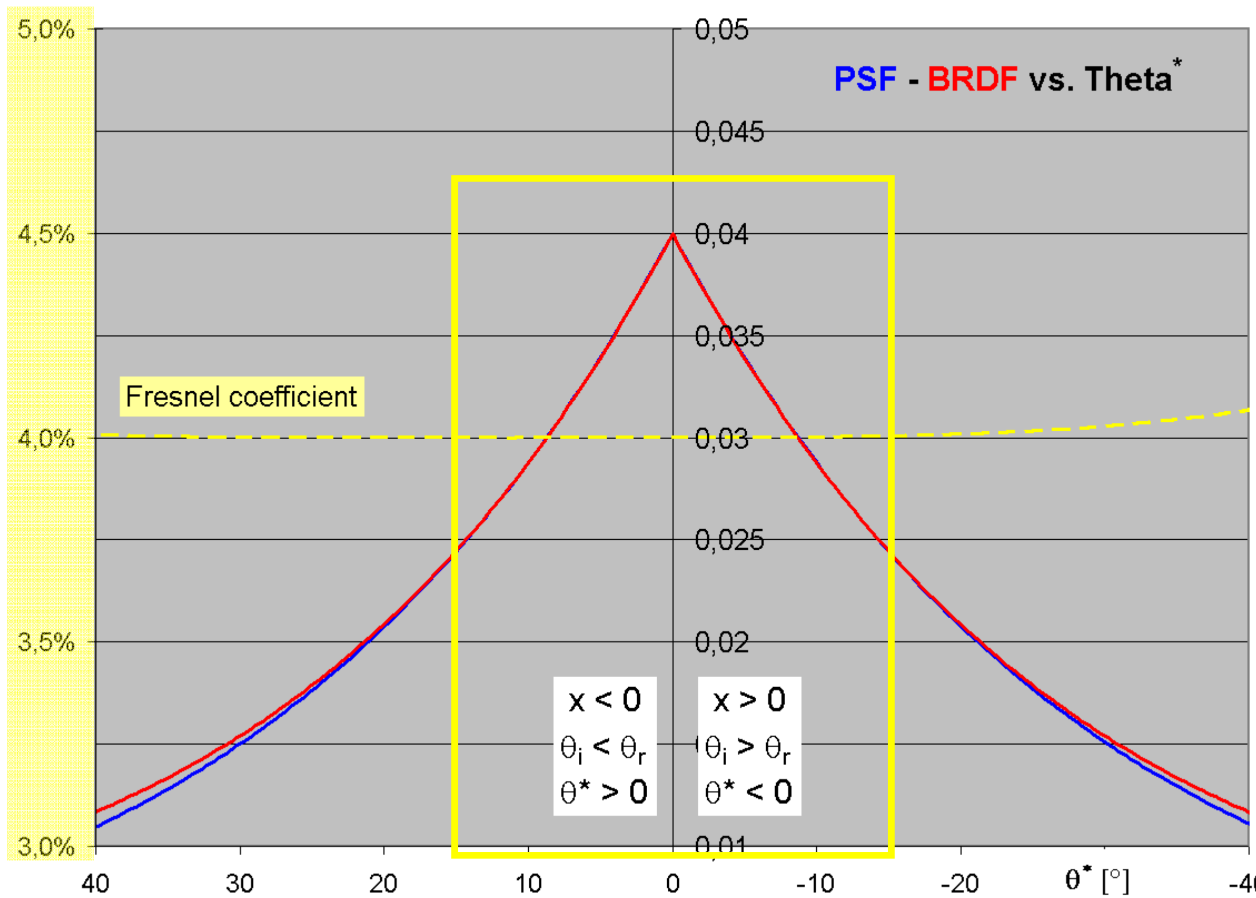
$$R = \frac{R_s + R_p}{2}$$

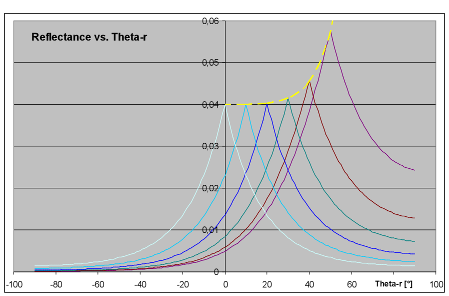


x_s = -25 mm, y_s = 250 mm
x_r = 25 mm, y_r = 250 mm

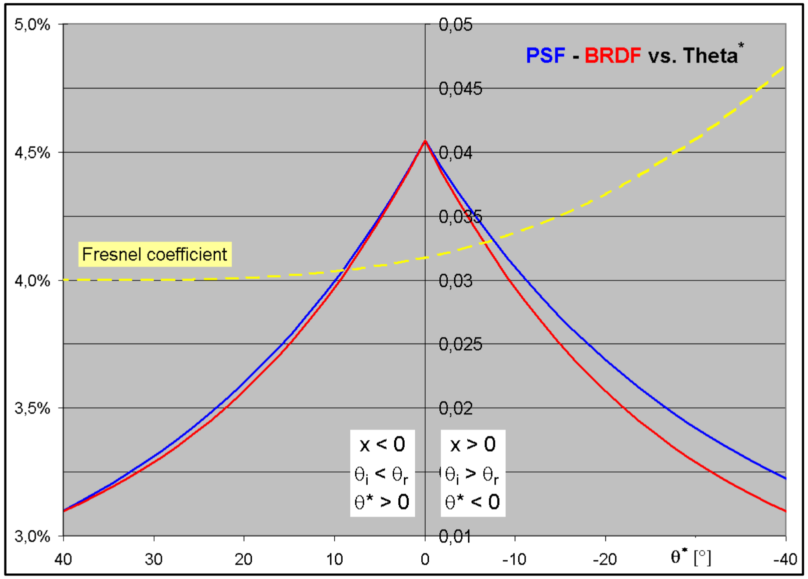
θ_i (x = 0) = 5,7°

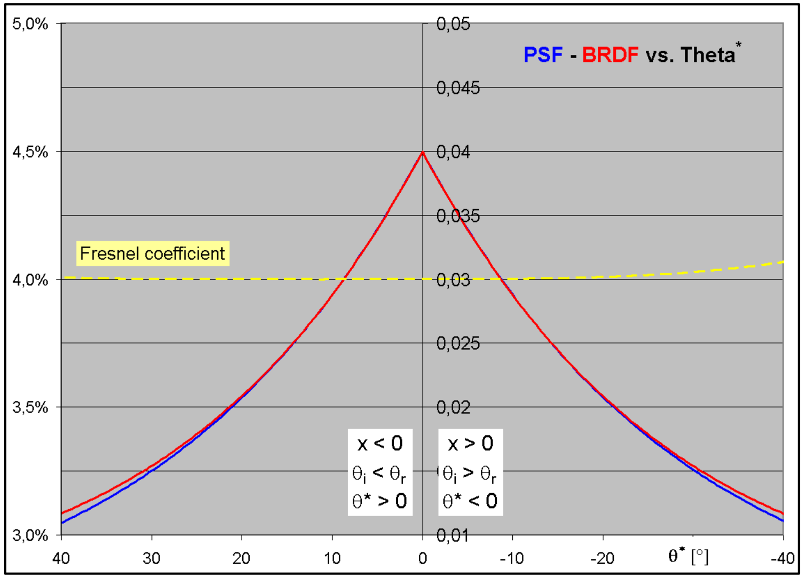
$$\mathrm{BRDF} = R(\theta_i) \cdot \exp\left(\left| \frac{\sin\theta_r - \sin\theta_i}{w} \right| \right)$$





PSF - LSF Analyis vs. Directional Scanning

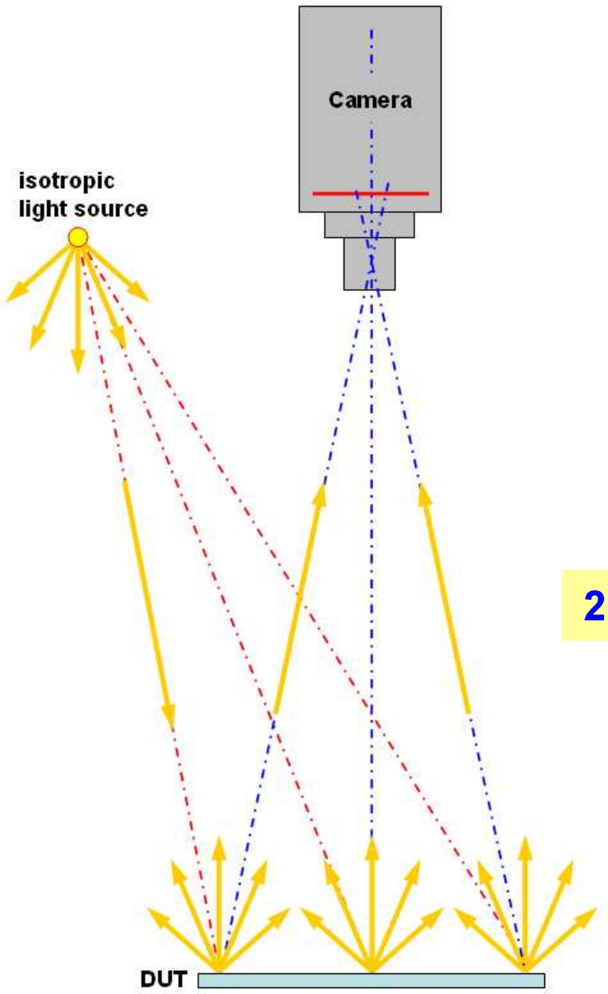




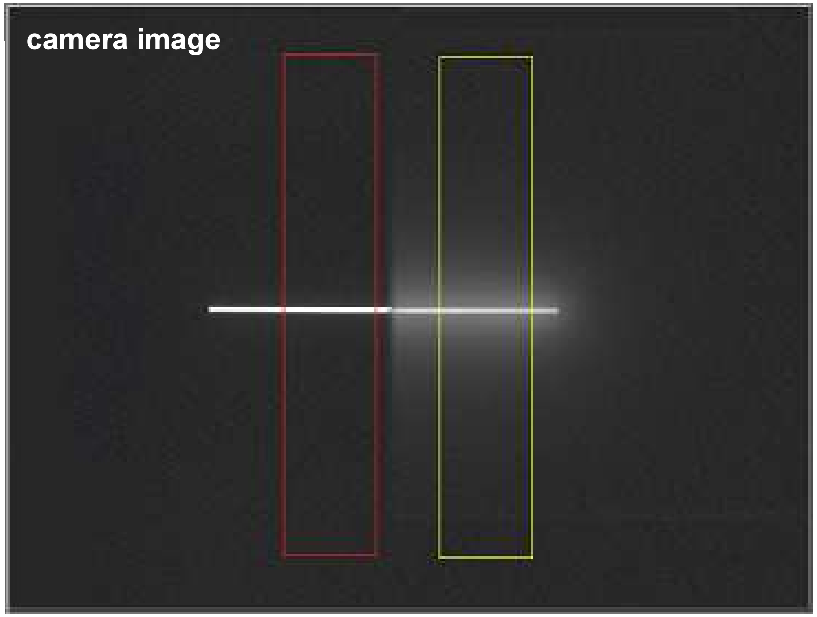
θ^* [°]			40	20	0	-20	-40	
Δ [%]	$\theta_i(x=0)=26°$		0,38	3,09	0,00	11,53	21,40	
θ^* [°]		15	10	5	0	-5	-10	-15
Δ [%]	$\theta_i(x=0)=5.6°$	-0,19	0,03	0,06	0,00	0,07	0,08	-0,07

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

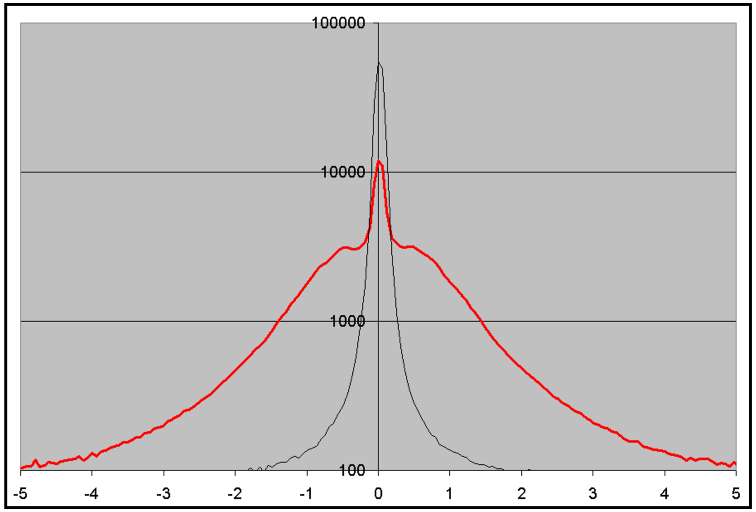
Analyis of Line-Spread Function



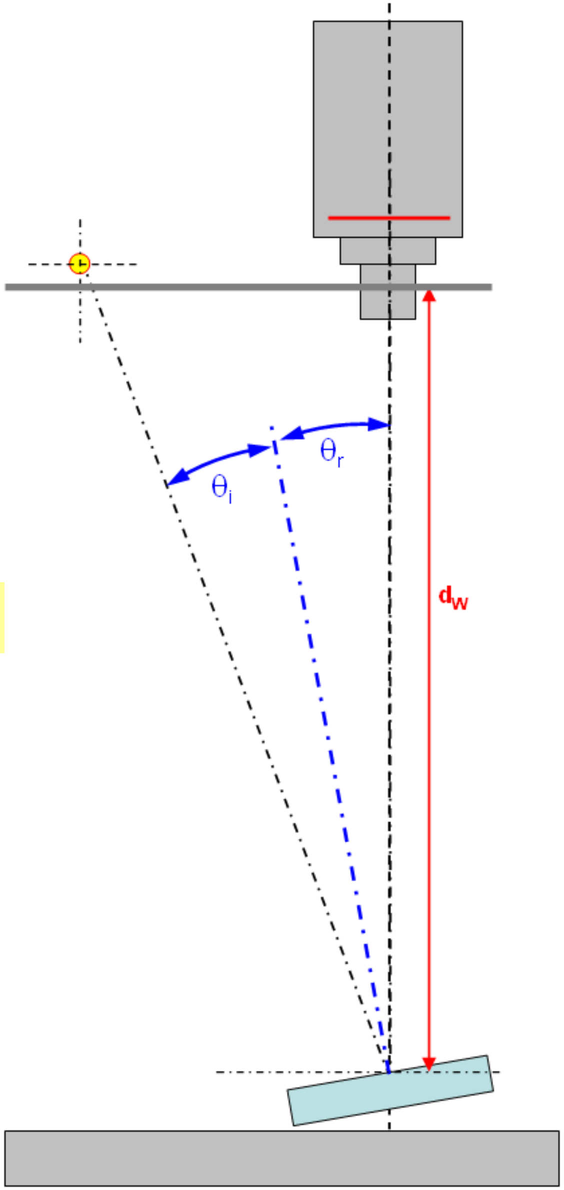
side view



2D geometry with narrow linear light source

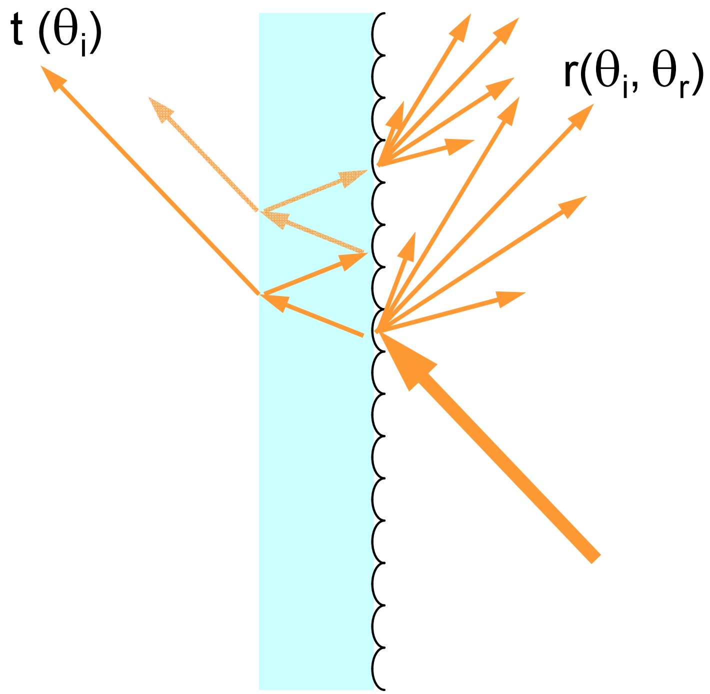


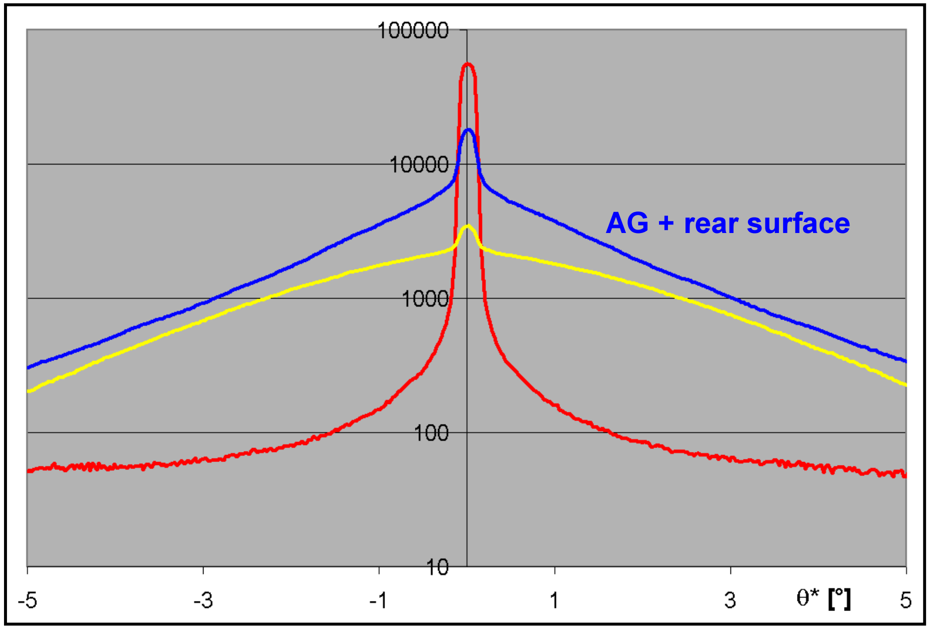
intensity profile, i = f(θ^*)



Variation with Angle of Incidence

Reflectance + Transmittance

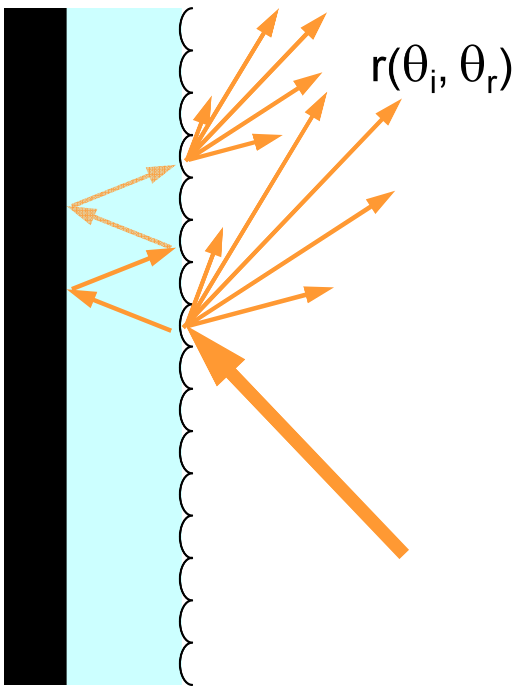


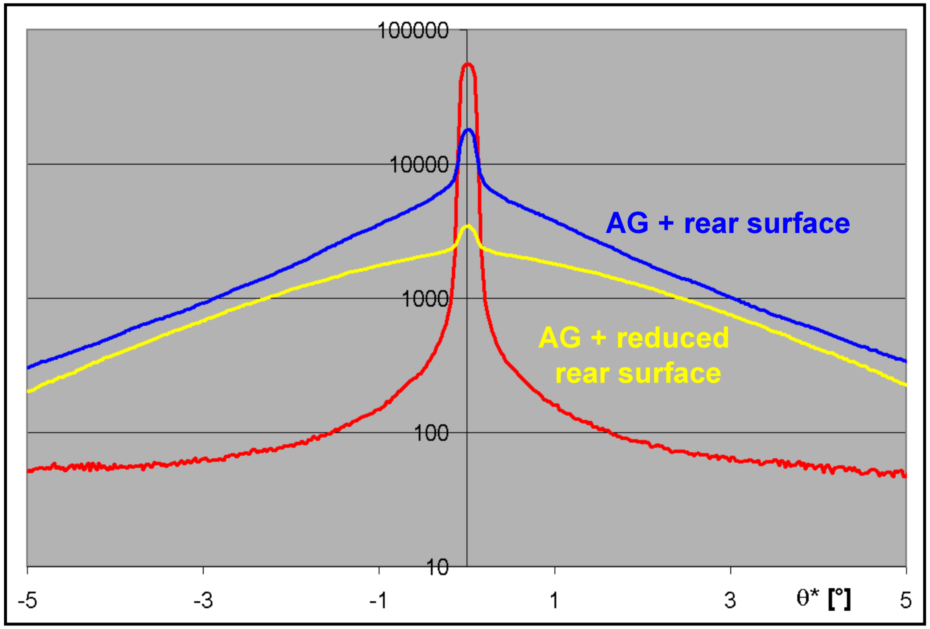


In the case of transparent/translucent layers reflection and transmission are closely coupled.

Reflectance distribution of an AG layer without (yellow curve) and with rear surface reflection (blue curve); the red curve shows the light source (system signature).

Reflectance + Transmittance

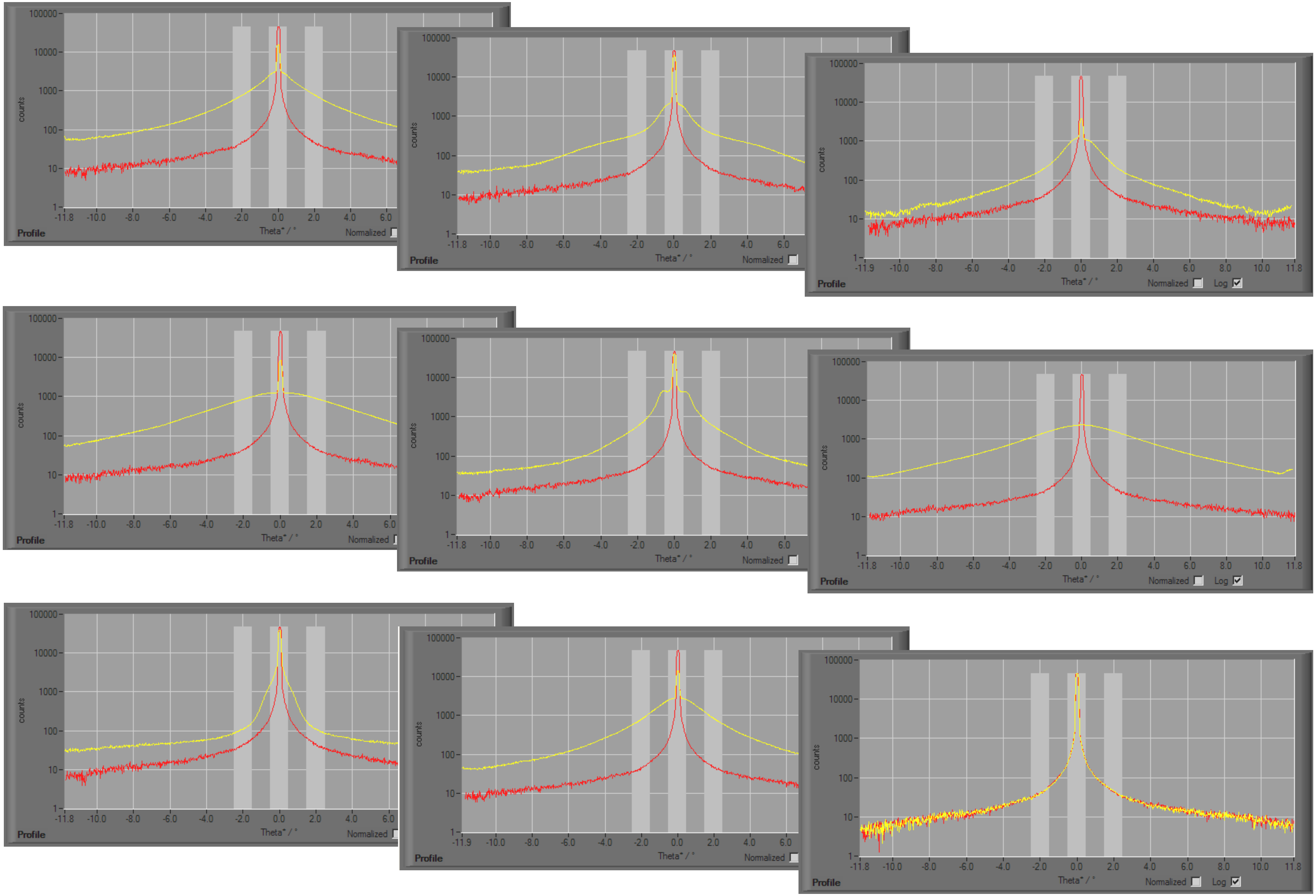


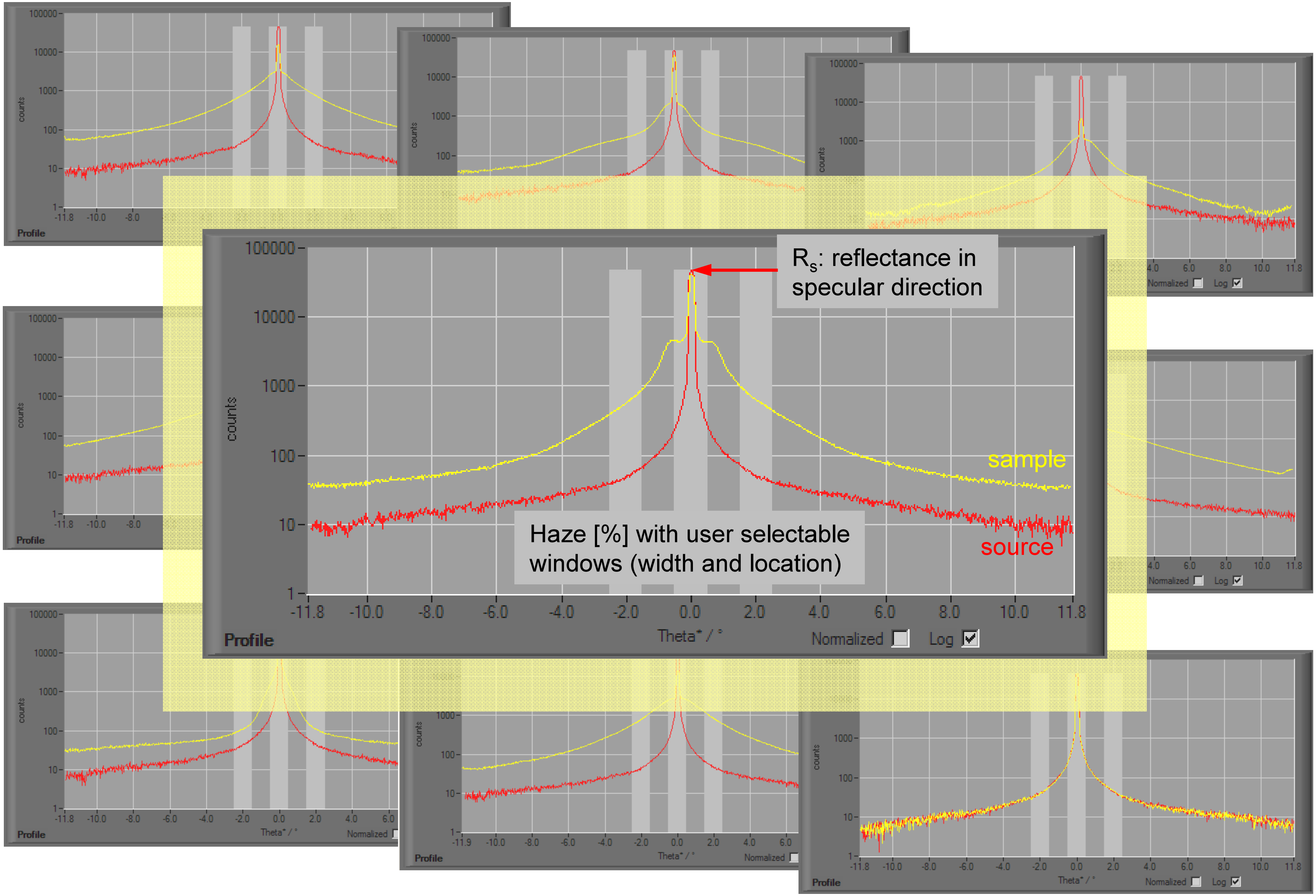


Black absorbing layer reduces reflections at the rear surface to ~10% of the original level.

Reflectance distribution of an AG layer without (yellow curve) and with rear surface reflection (blue curve); the red curve shows the light source (system signature).

Reflectance Distribution Function





R_s: reflectance in specular direction
Haze [%] with user selectable windows (width and location)
sample
source
counts
Profile
Theta* / °
Normalized
Log

Directional Scanning by PSF / LSF Analysis

- simple compact measurement setup without moving parts
  ➔ robust apparatus and procedure
- centered about the specular direction
  ➔ never miss the specular peak !
- iLMD images directly show "what's going on"

- very high directional resolution (improvement of ~10)
  and wide range of directions (cylinder geometry)

- colorimetric analysis via iLMD or illumination

Requirements & Limitations

- sample must be uniform over area included in the measurement
- limited range of inclinations centered about specular or
- wide angular range at reduced resolution (cylinder).

Verification by model calculations and other instruments

Proc. SID 2016

High-Resolution Scatter Measurement and Evaluation

Our **model calculations** show that the effect of the variation of the Fresnel reflection coefficient and that of the shape asymmetry of the reflectance distribution function with angle of incidence on the results obtained by PSF/LSF analysis is negligible for geometries of practical importance, i.e. when a limited angular range about the specular direction (e.g. up to ±20°) is evaluated for small angles of light incidence (i.e.< 15°).

We thus conclude that scatter evaluation based on analysis of point-spread and/or line-spread functions (reflective and transmissive case) is well suited for accurate, fast and robust evaluation of the glossy scatter of AG layers.

Colorimetric analysis is possible with either monochromatic light sources or with imaging colorimeters in combination with white light sources.

PSF and LSF analysis with imaging photometers thus offers a realistic alternative to conventional directional scanning with goniometric or conoscopic instruments due to the reduced instrumental efforts without moving parts or demanding optical systems.

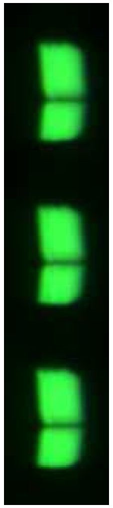
This approach offers easy alignment of the setup with adaptation to a wide range of incidence angles and fast measurements in combination with high directional resolution.

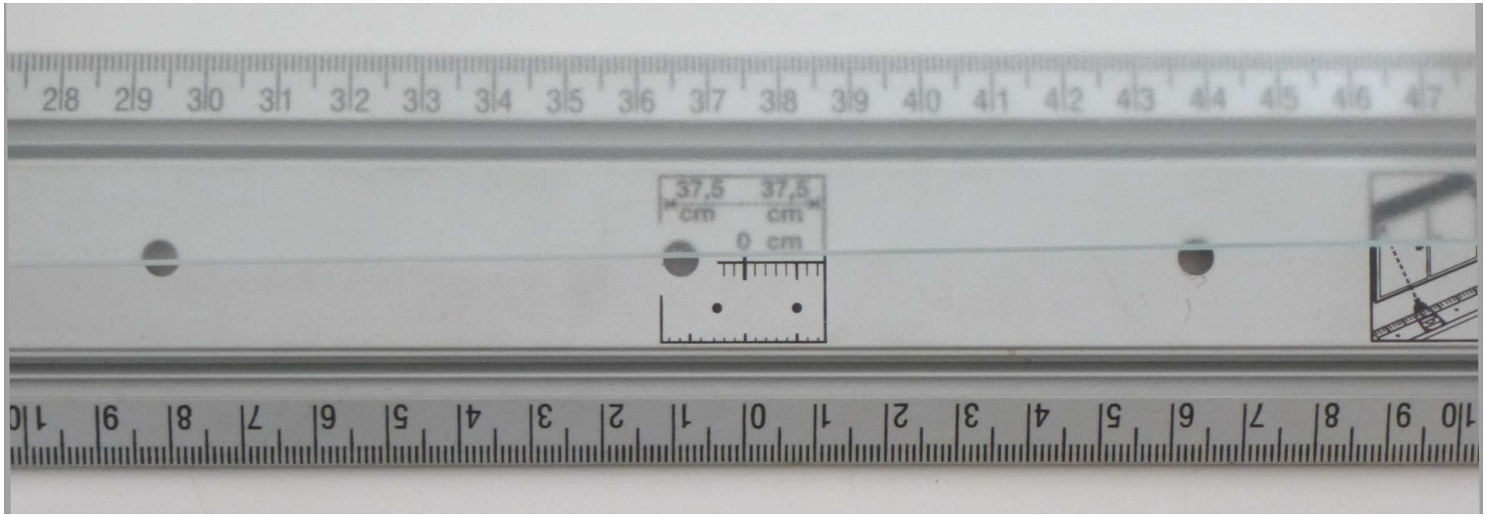
The required uniformity of the samples across the surface area included in the measurement is required anyway for uniform optical appearance of electronic display devices.

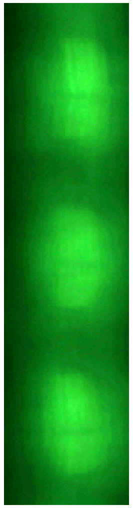
Image Blur

Induced by Scattering Anti-Glare Layers

distinctness of image - image clarity - image blur





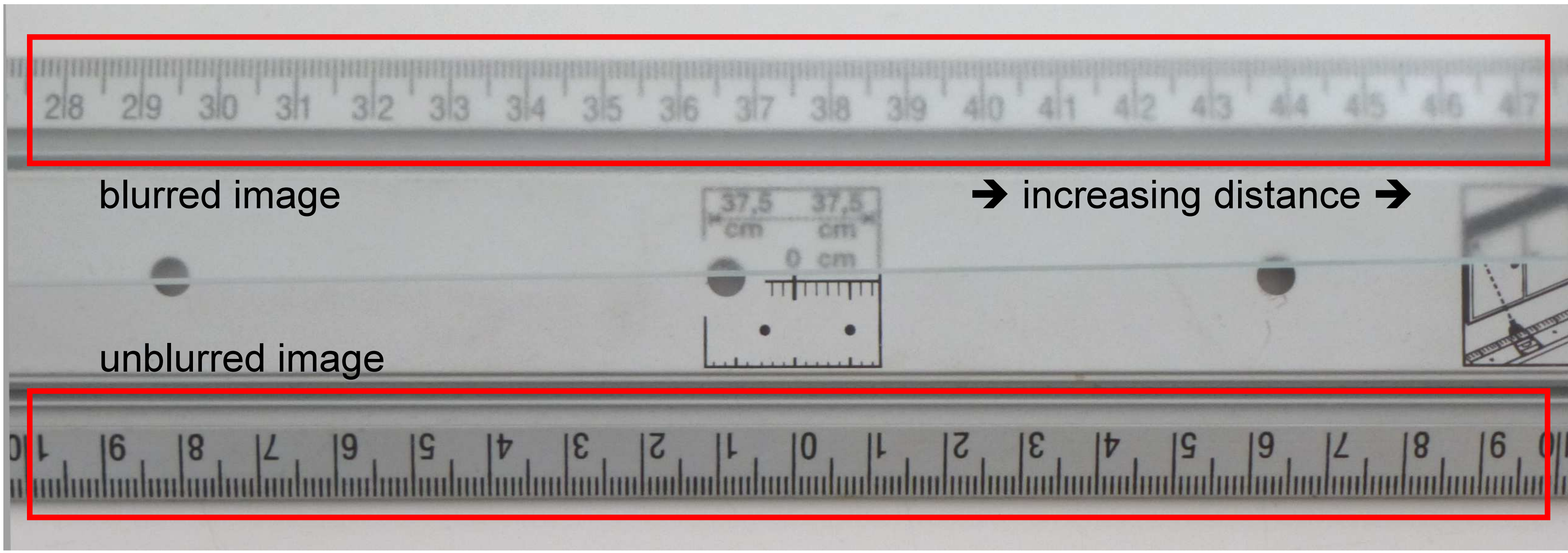


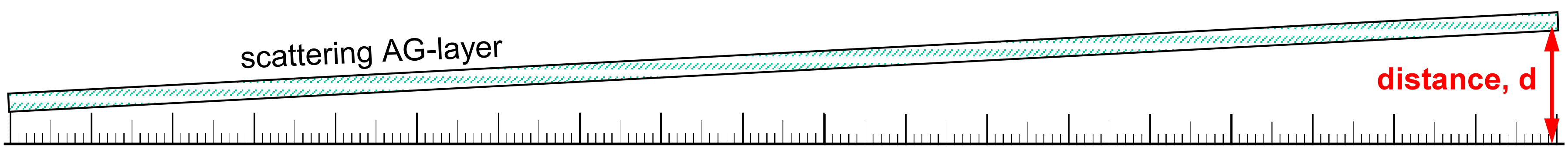
M. E. Becker, T. Fink, U. Krüger: Image Blurring Induced by Scattering Anti-Glare Layers, Proc. SID2016

Image Blur

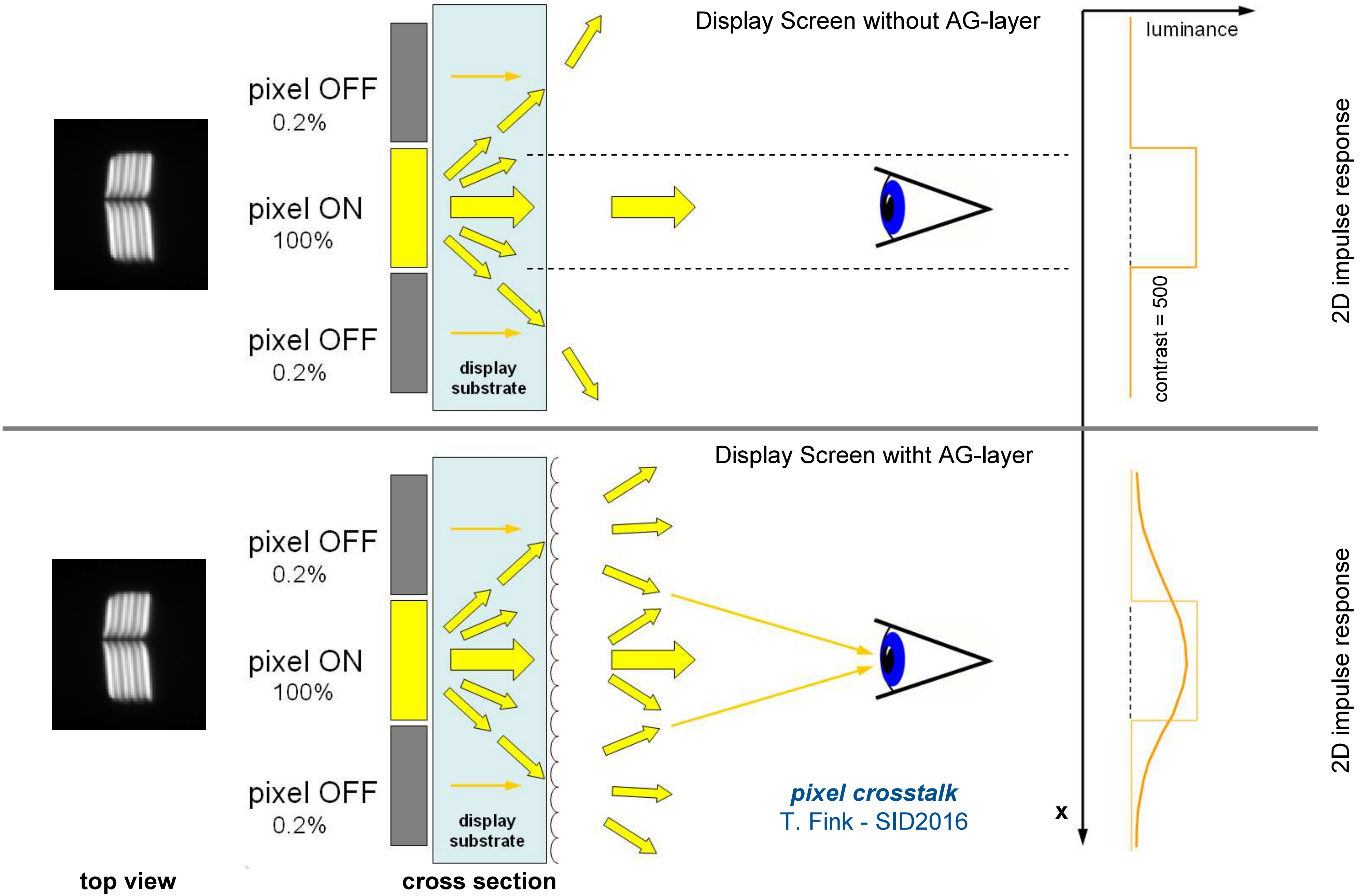
Micro-structured, scattering anti-glare layers reduce mirror images,

but they also reduce ***distinctness of (transmitted) image*** (DOI), image clarity, ...



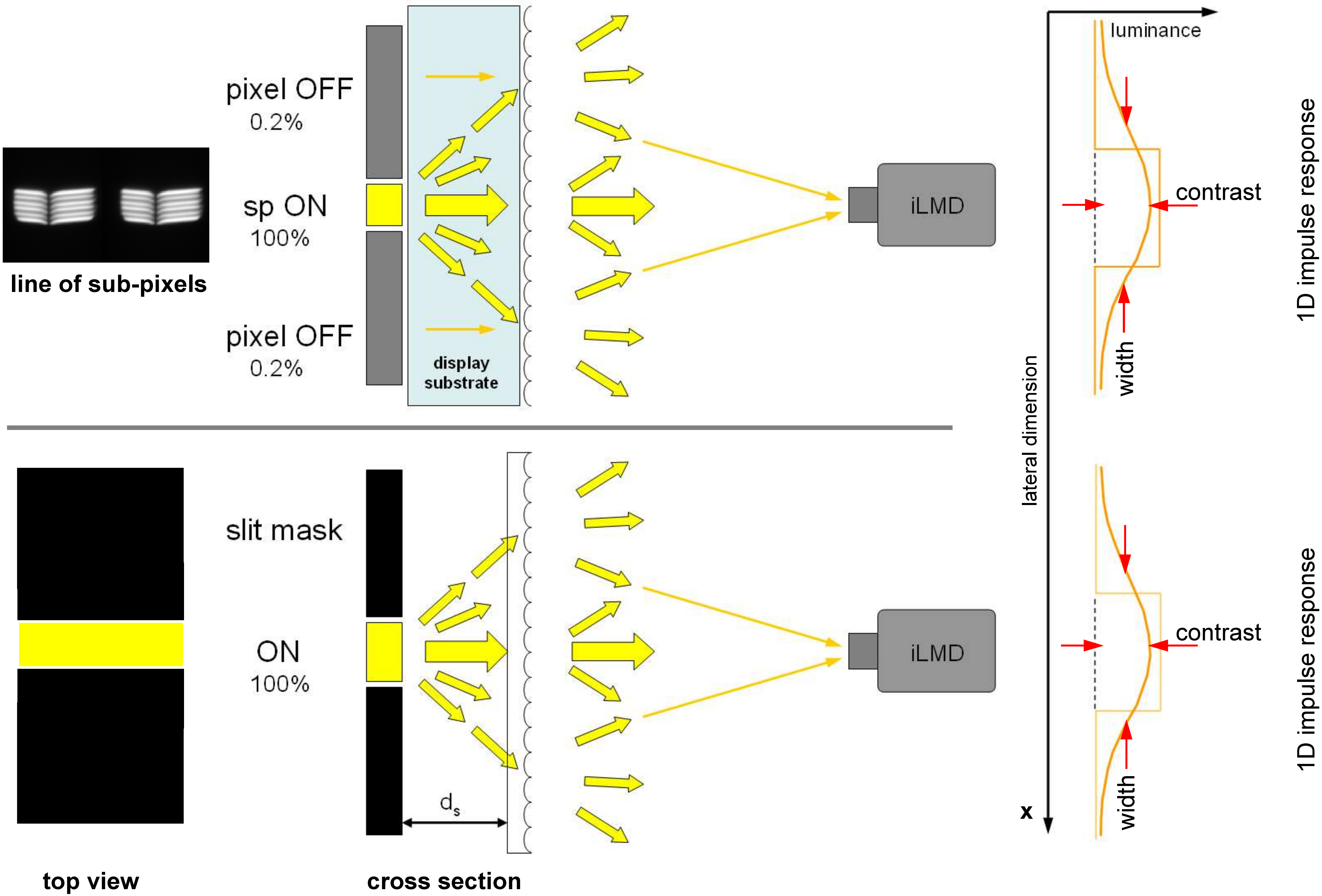


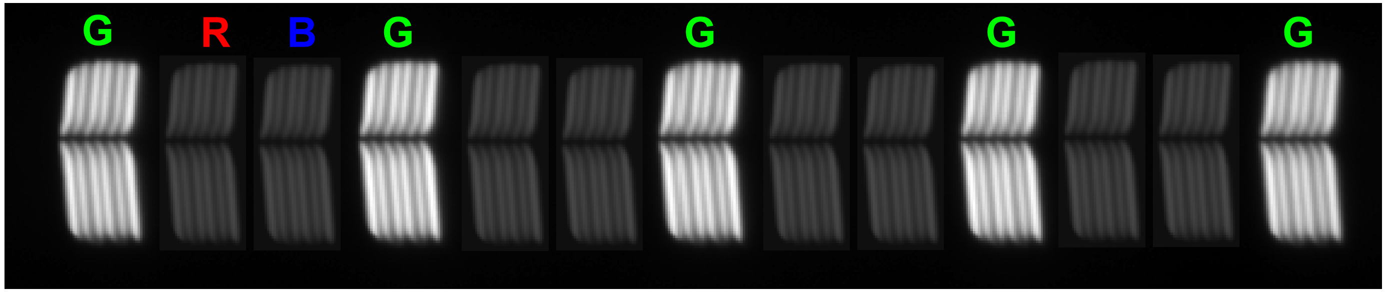
Pixel Crosstalk



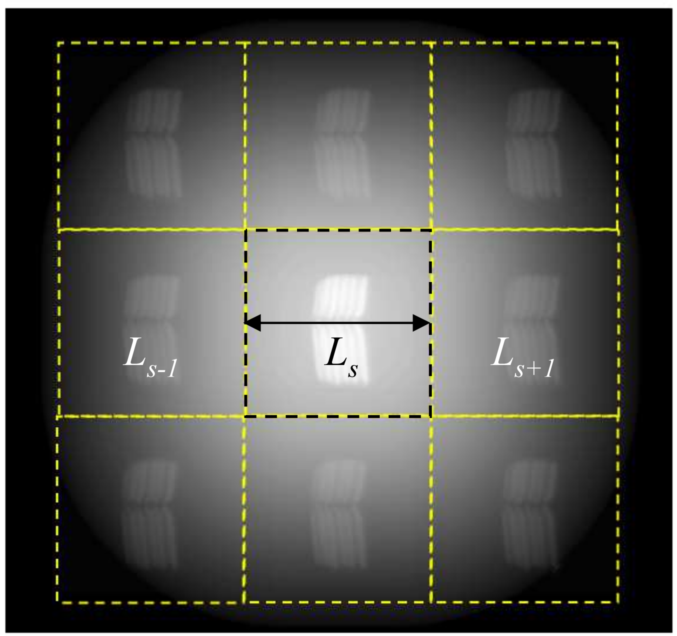
pixel crosstalk
T. Fink - SID2016

Measurement Setup



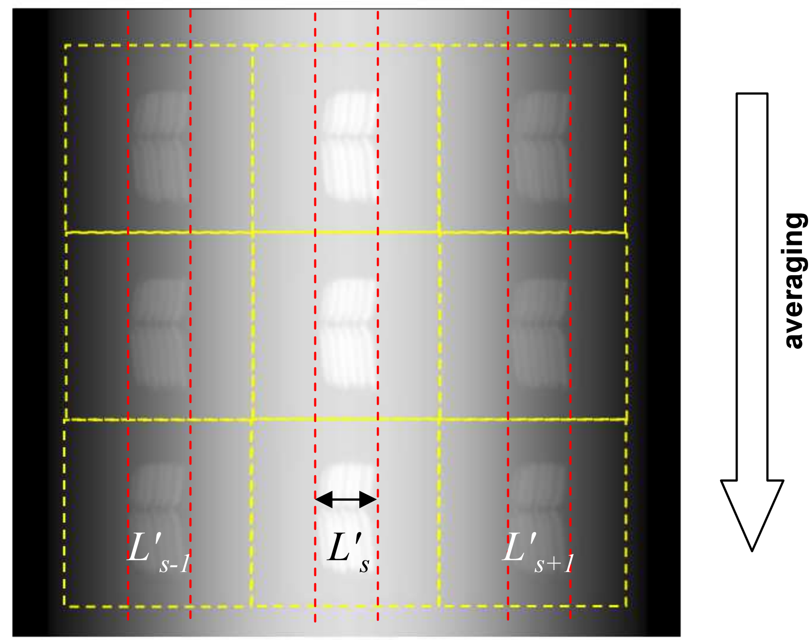


pixel crosstalk, PCT



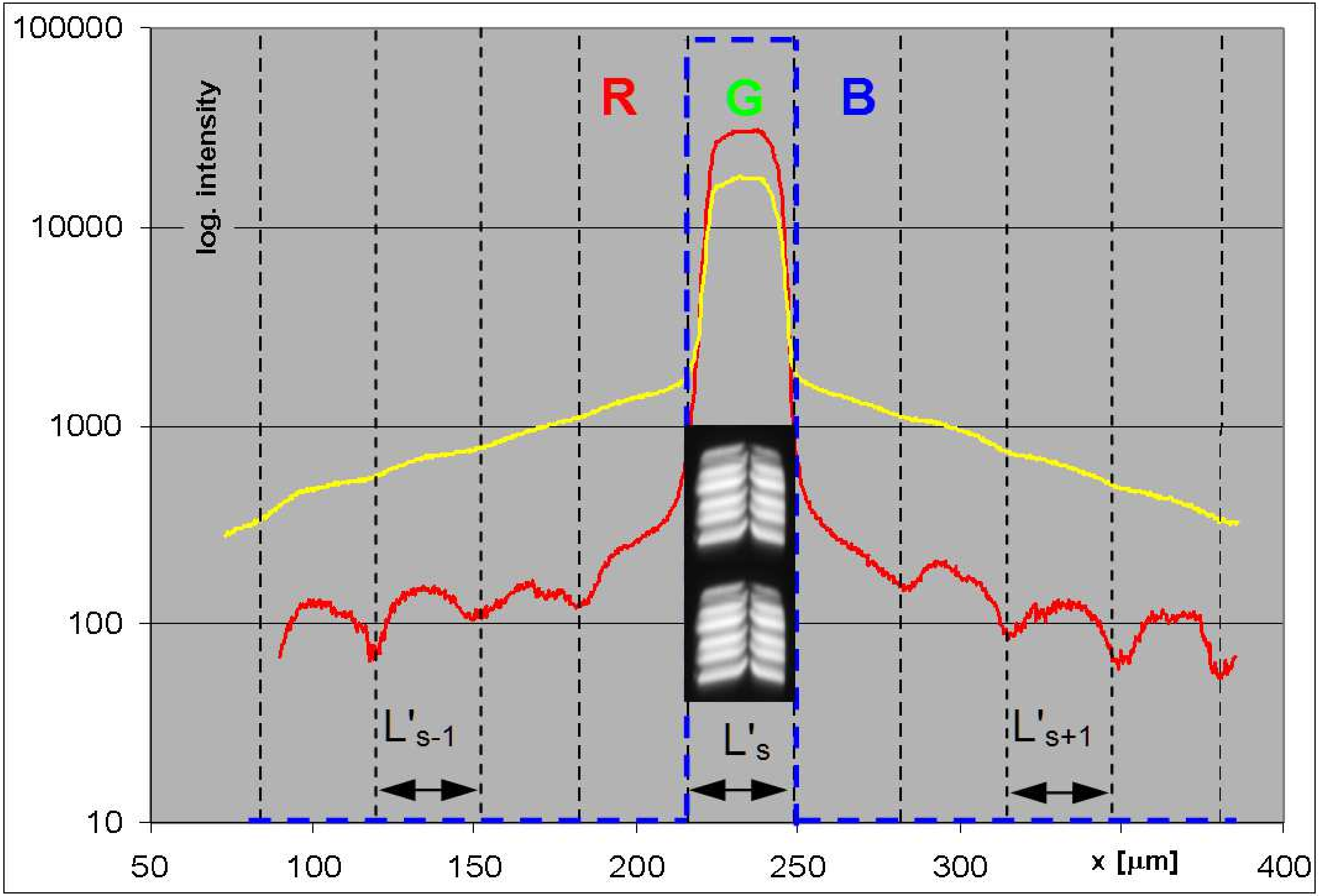
$$PCT = \frac{L_{s-1} + L_{s+1}}{2 \cdot L_s}$$

line spreading level, S_{LS}



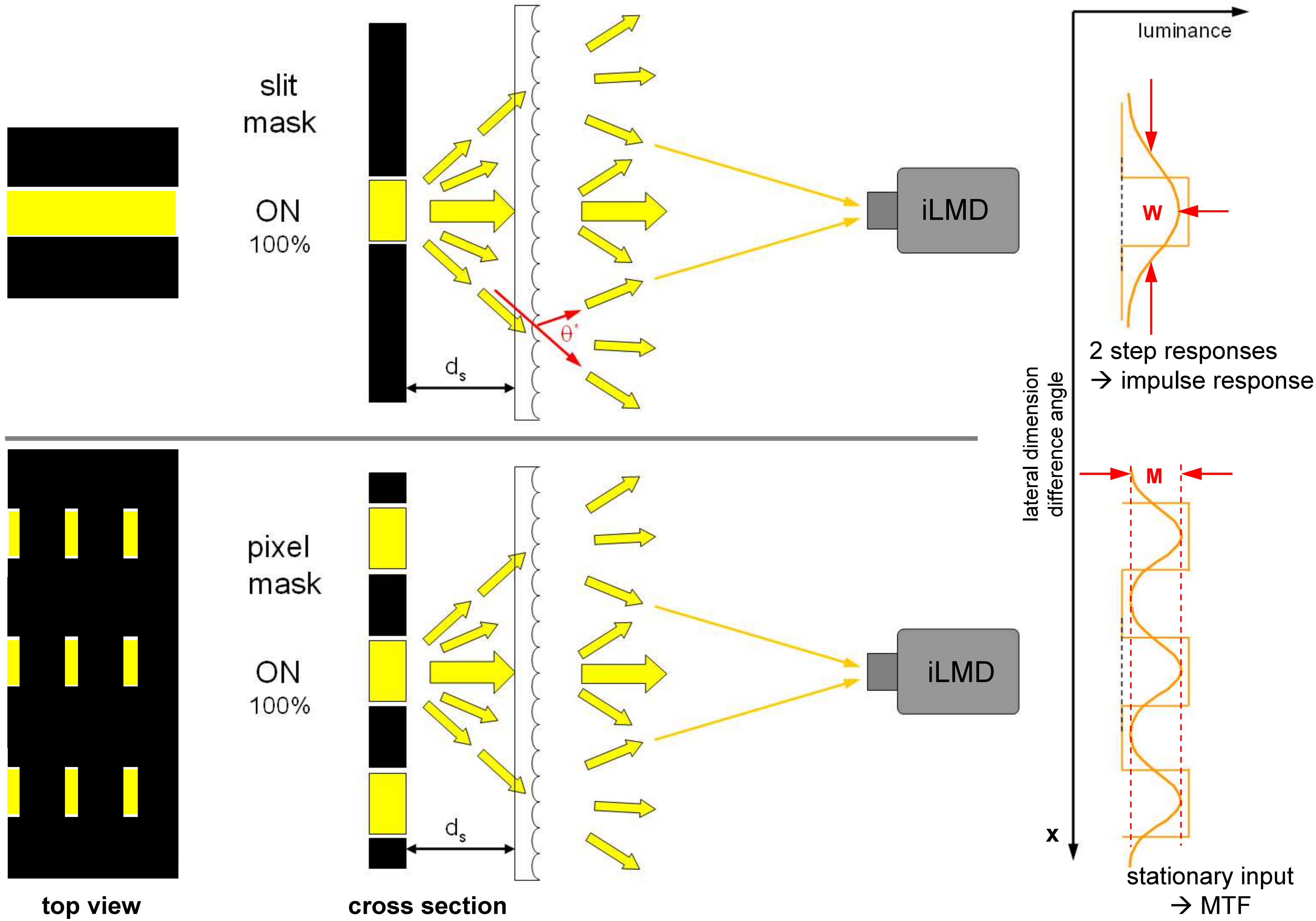
$$S_{LS} = \frac{L'_{s-1} + L'_{s+1}}{2 \cdot L'_s}$$

Pixel-Crosstalk - Line Spreading

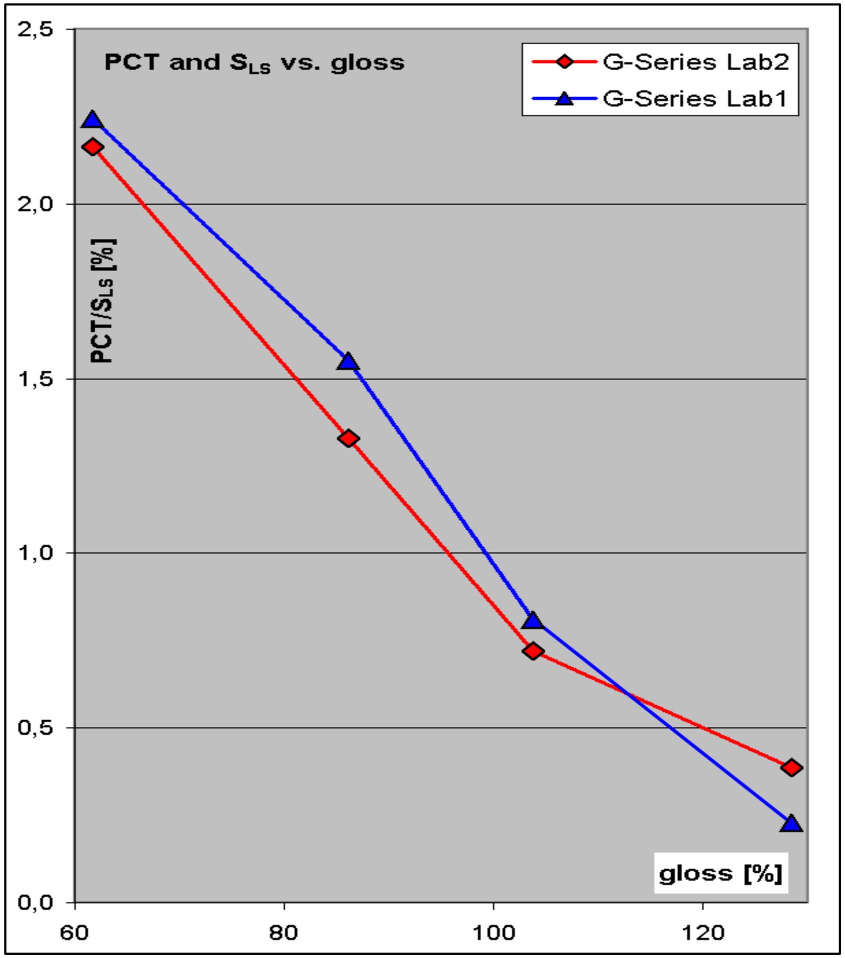


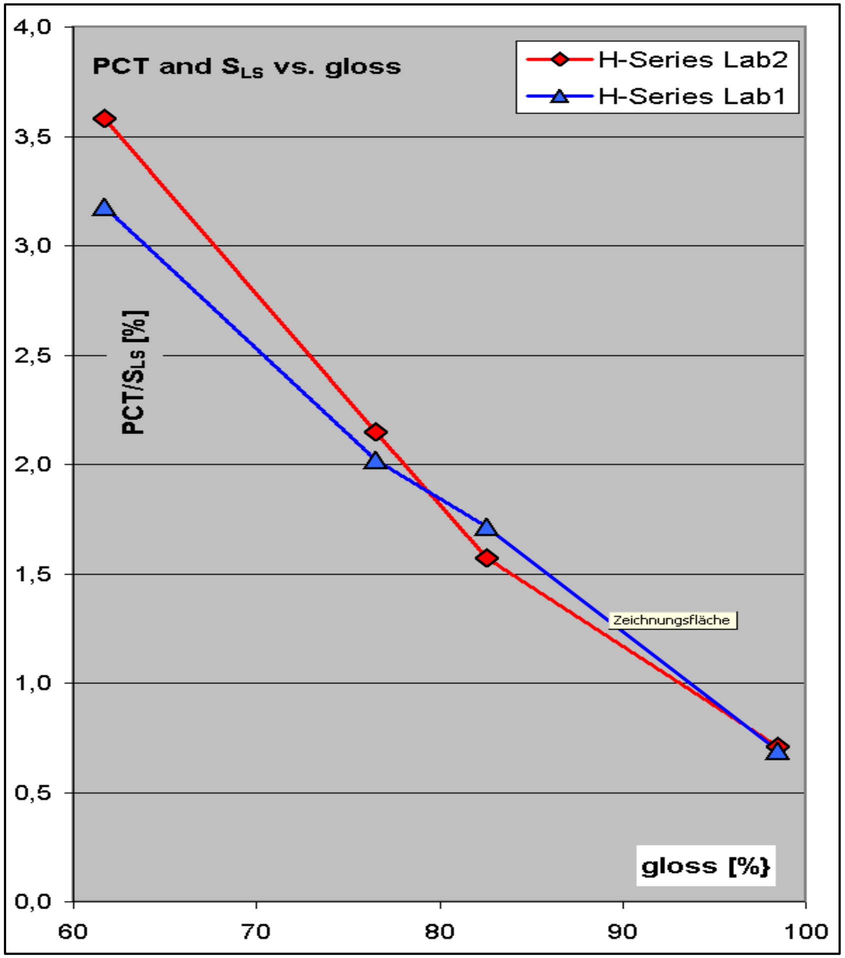
Horizontal intensity profiles of activated green subpixels of a non-scattering display screen (0.10 mm pixel pitch, with touch panel) recorded with a microscope objective lens.
Red curve: green subpixel column without AG-layer. Yellow curve: green subpixels with AG-layer.
Blue curve: a pulse illustrating the ideal subpixel profile.

Measurement Setup



Pixel-crosstalk vs. line spreading

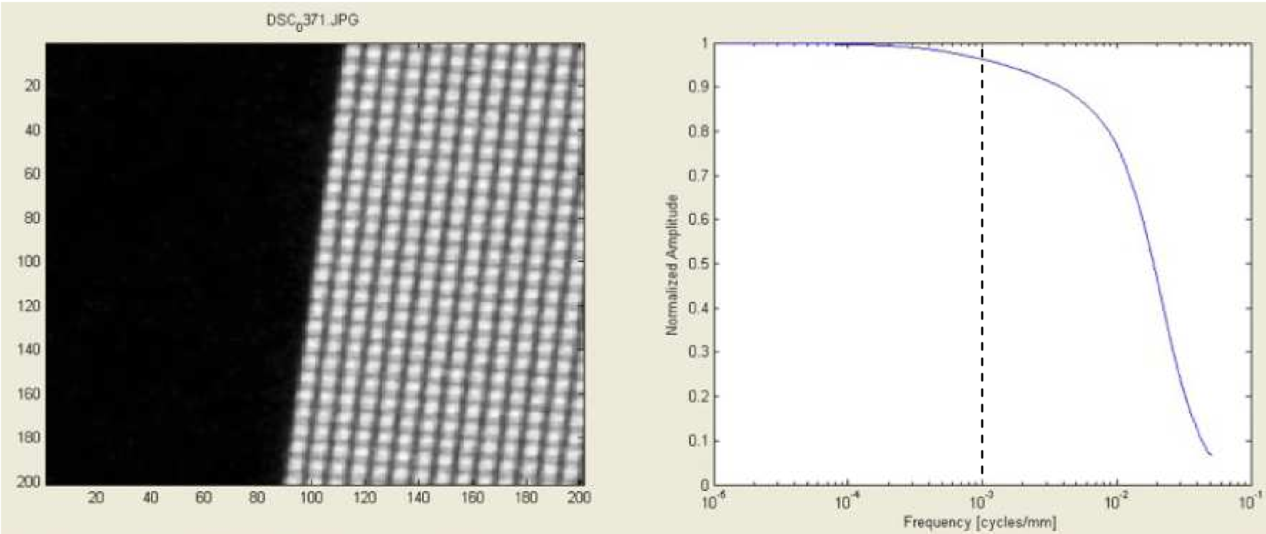


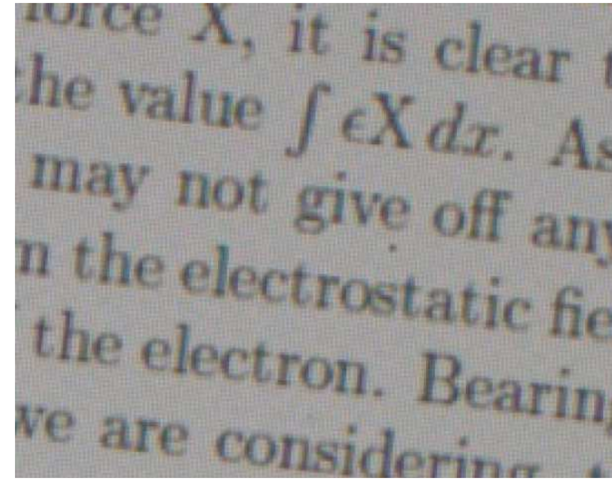


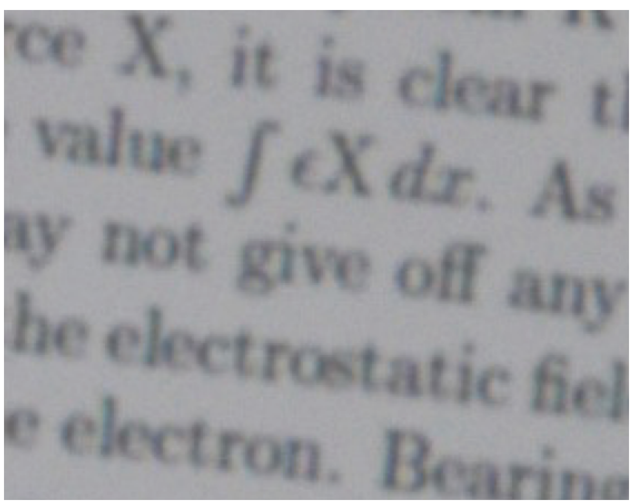
Pixel-crosstalk, PCT, and line spreading levels, S_{LS}, evaluated for eight AG-samples by the authors in two laboratories (Lab-1, Lab-2) with two different instrumental arrangements plotted vs. reflection gloss (specifications of the manufacturer).

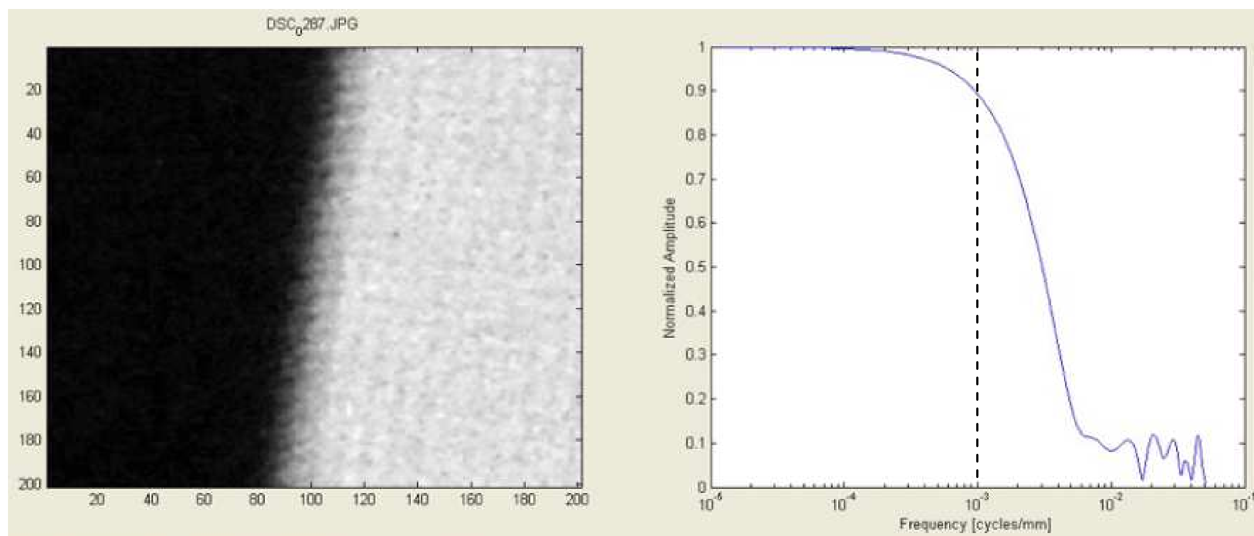
M. E. Becker, T. Fink, U. Krüger: Image Blurring Induced by Scattering Anti-Glare Layers, Proc. SID2016

Slanted edge method - ISO 12233 (step analysis)









From: 3M AG/AS: A single-film solution to glare and sparkle in HD displays

Pixel crosstalk

2D impulse response

introduced by Dr. Fink @ SID2016

Line spread analysis

1D impulse response

introduced here

↑

distance source - AG-layer

↓

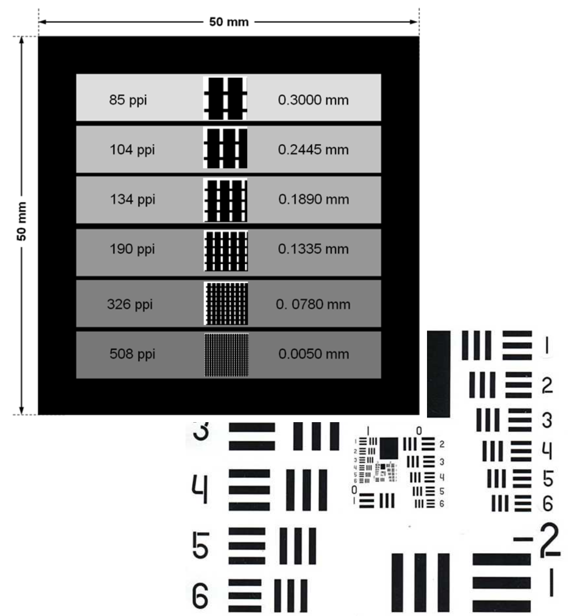
Transmission distribution function

- line spread analysis
- conoscopic imaging

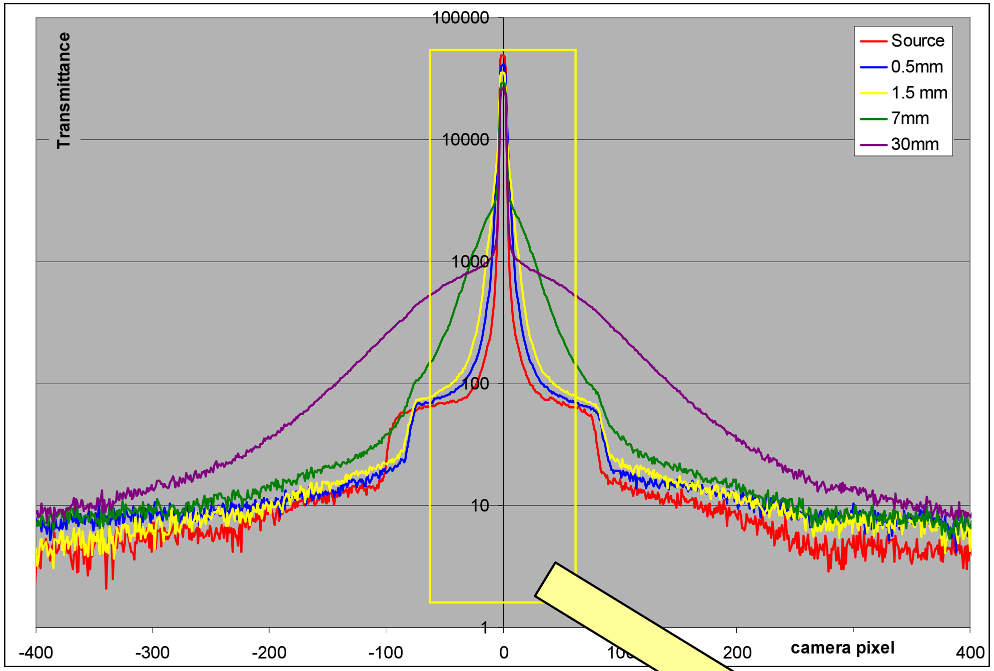
Modulation transfer factor or function

- stationary input (grating)

Slanted edge method (step analysis)



Line Spreading vs. Distance

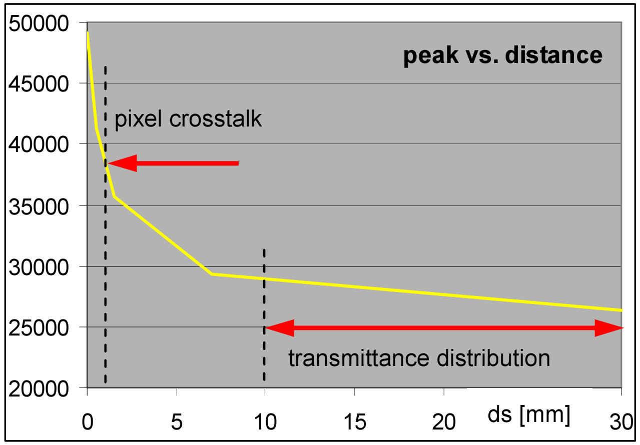


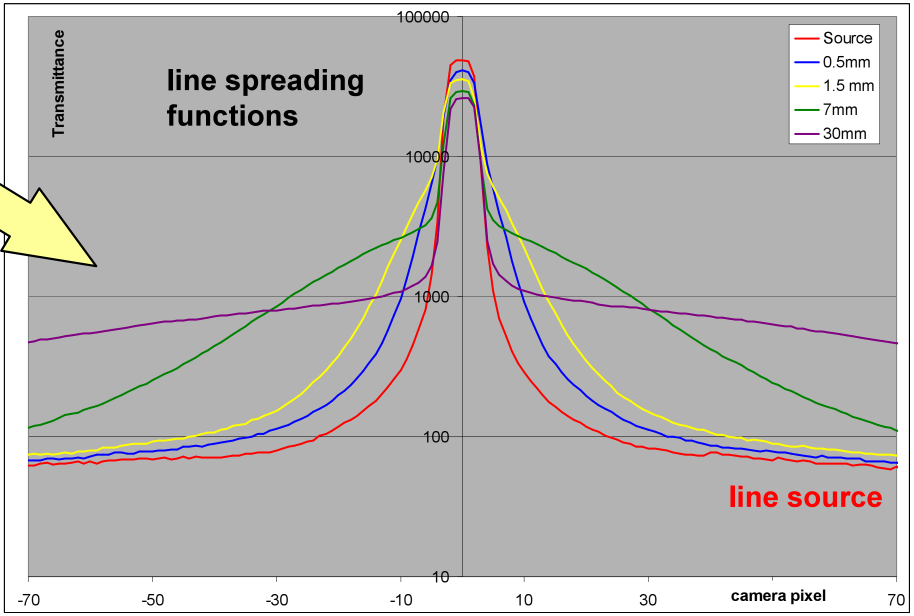
AG layer close to pixel matrix:
➔ *pixel crosstalk*

increasing distance, d_s:
➔ *transmittance distribution*

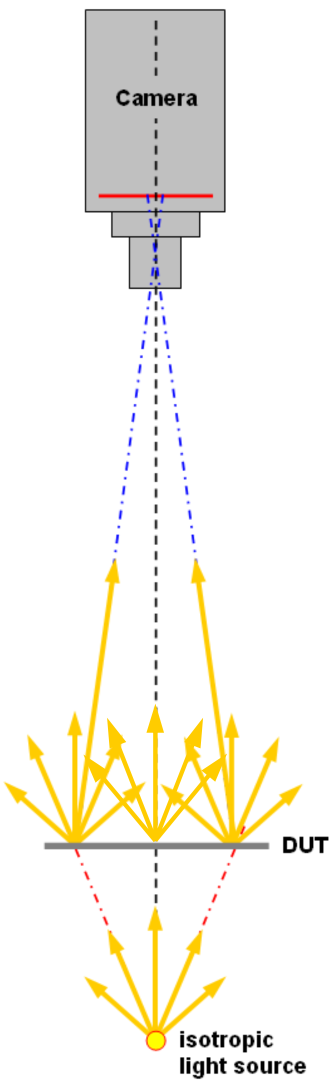
general: *line spreading function*

same AG layer, transmittance distribution vs. distance to line source, d_s

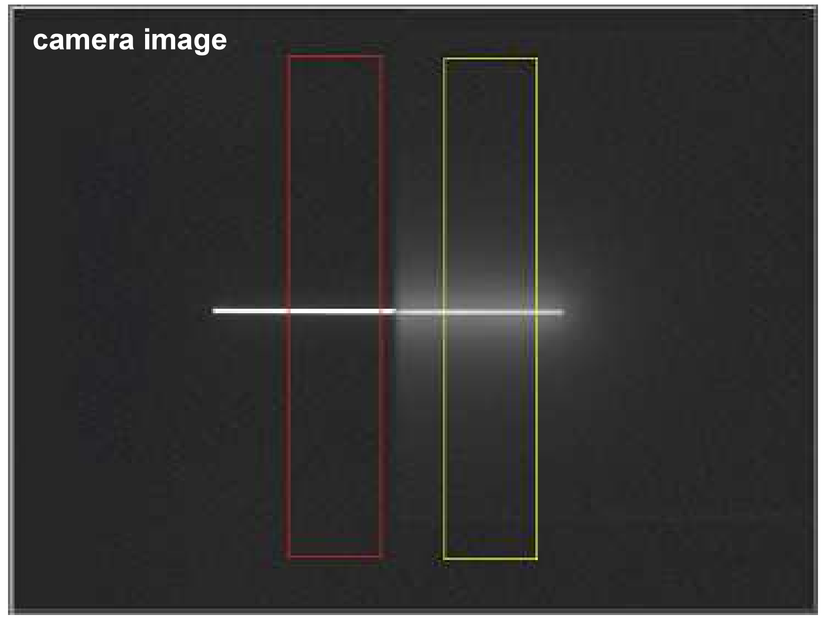




Transmittance Distribution Function



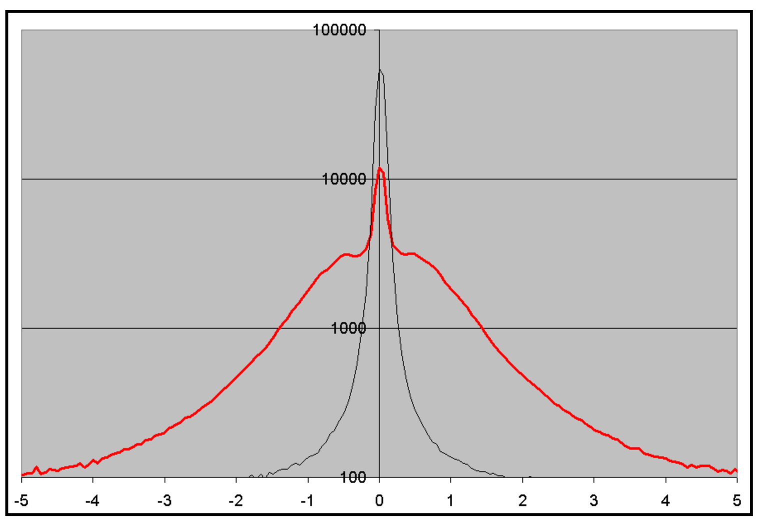
side view



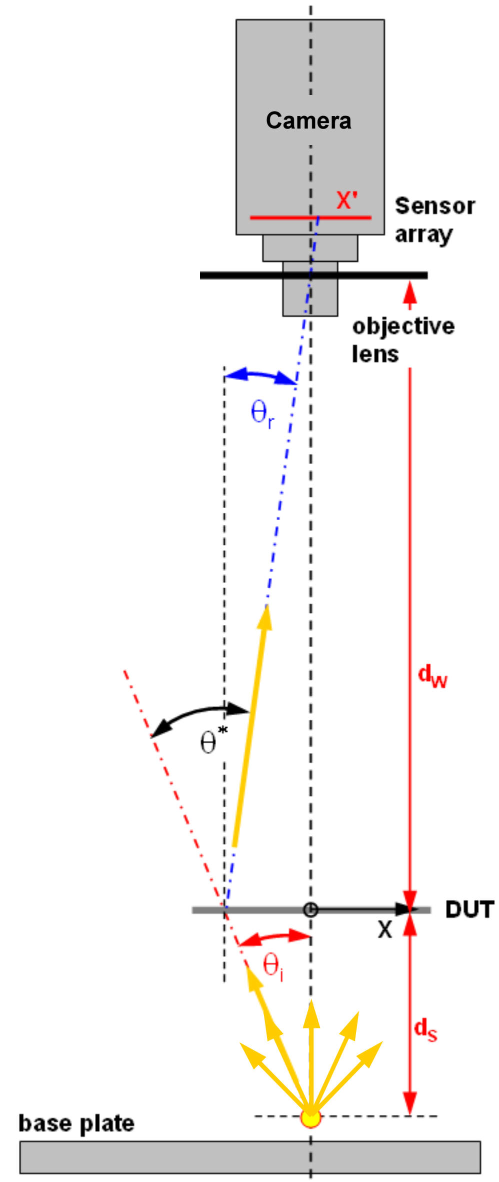
2D geometry with narrow linear light source

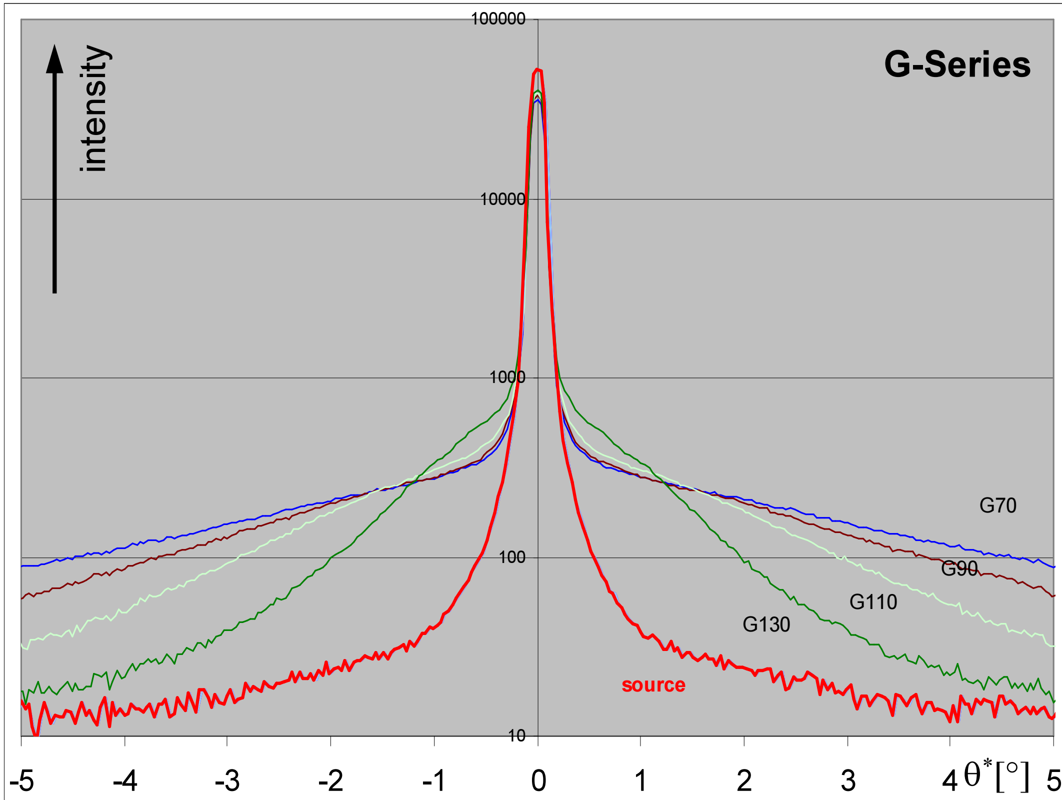
transmitt.
distr. function

pixel
crosstalk



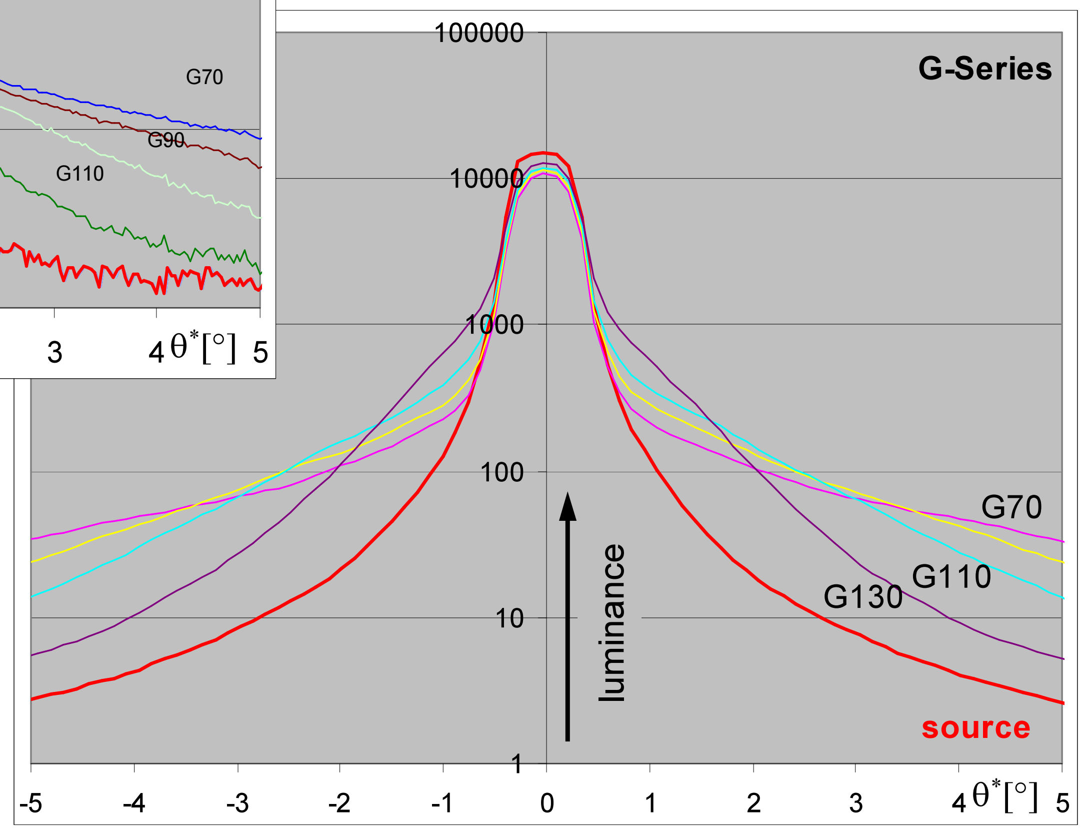
intensity profile, $i = f(\theta^*)$





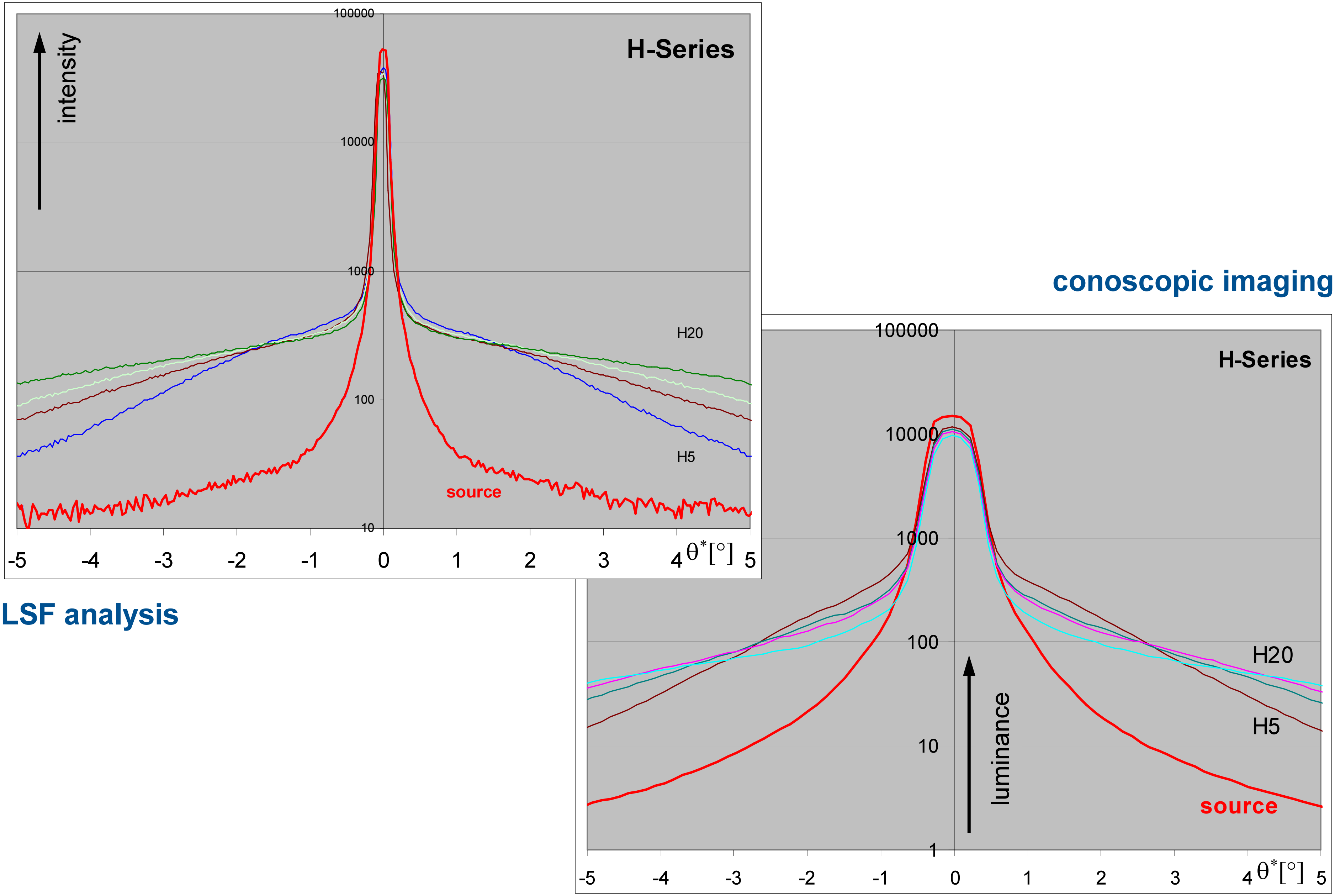
LSF analysis

conoscopic imaging



M. E. Becker, T. Fink, U. Krüger: Image Blurring Induced by Scattering Anti-Glare Layers, Proc. SID2016

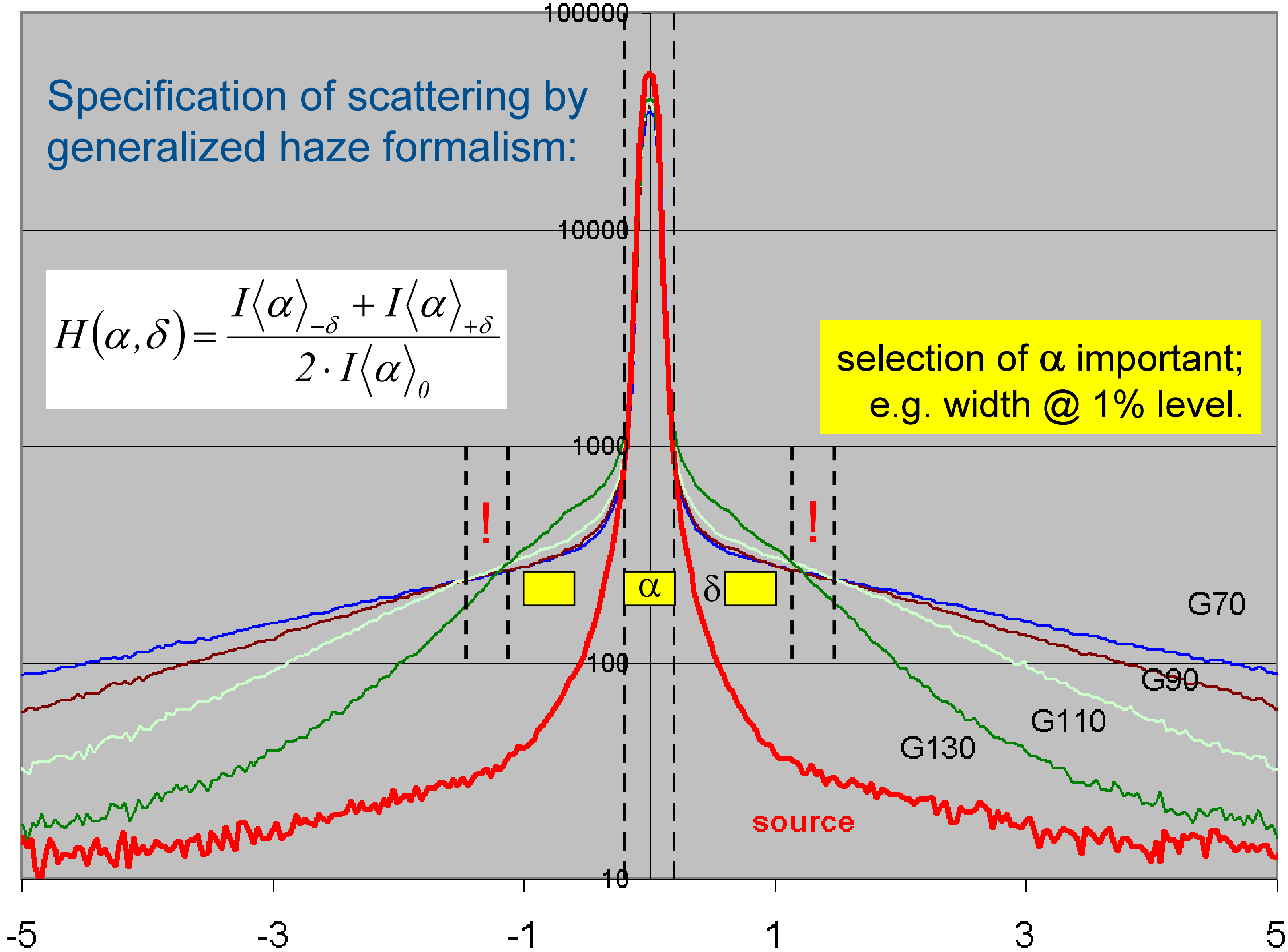
Scatter Distribution Functions



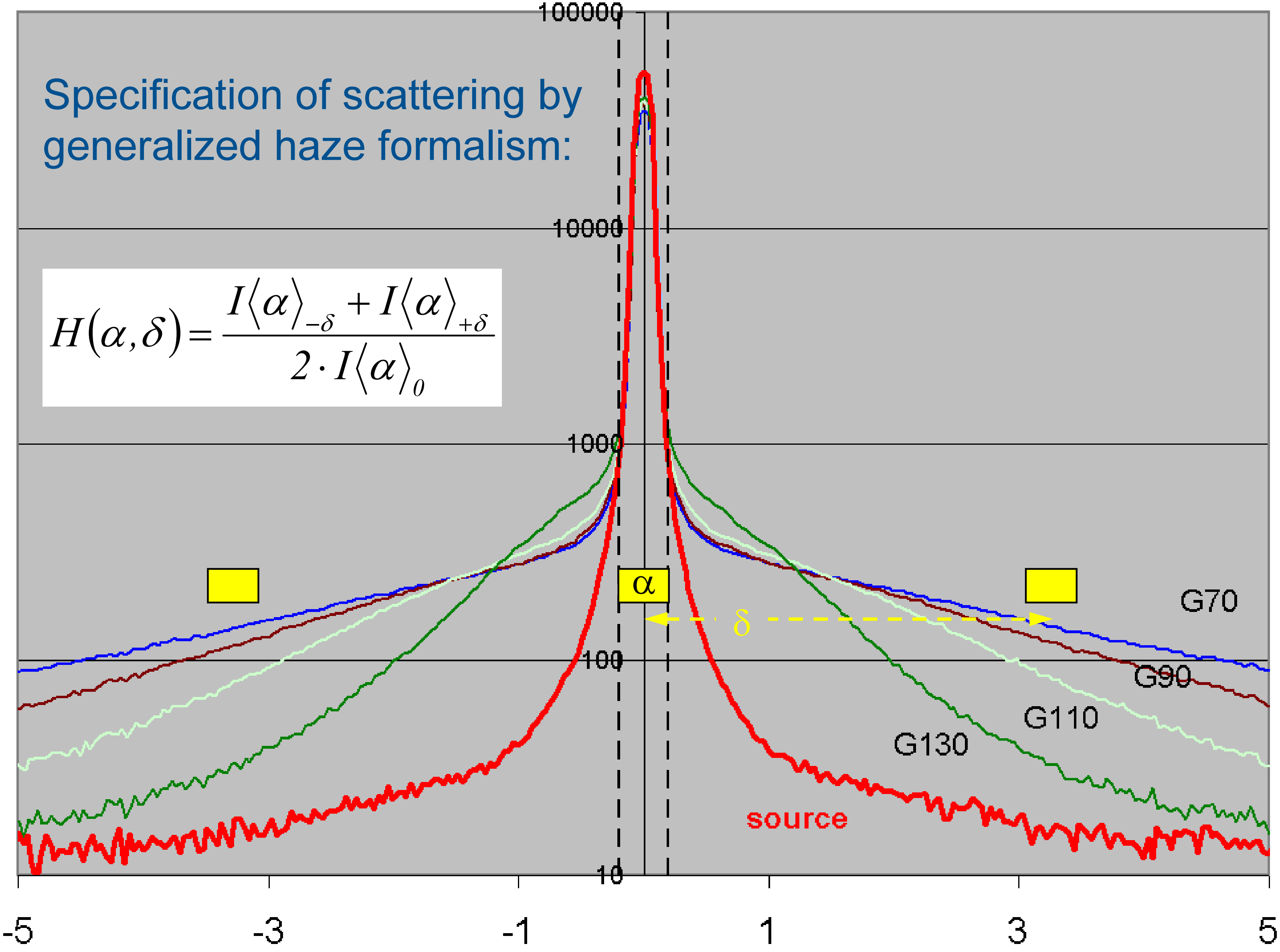
LSF analysis

M. E. Becker, T. Fink, U. Krüger: Image Blurring Induced by Scattering Anti-Glare Layers, Proc. SID2016

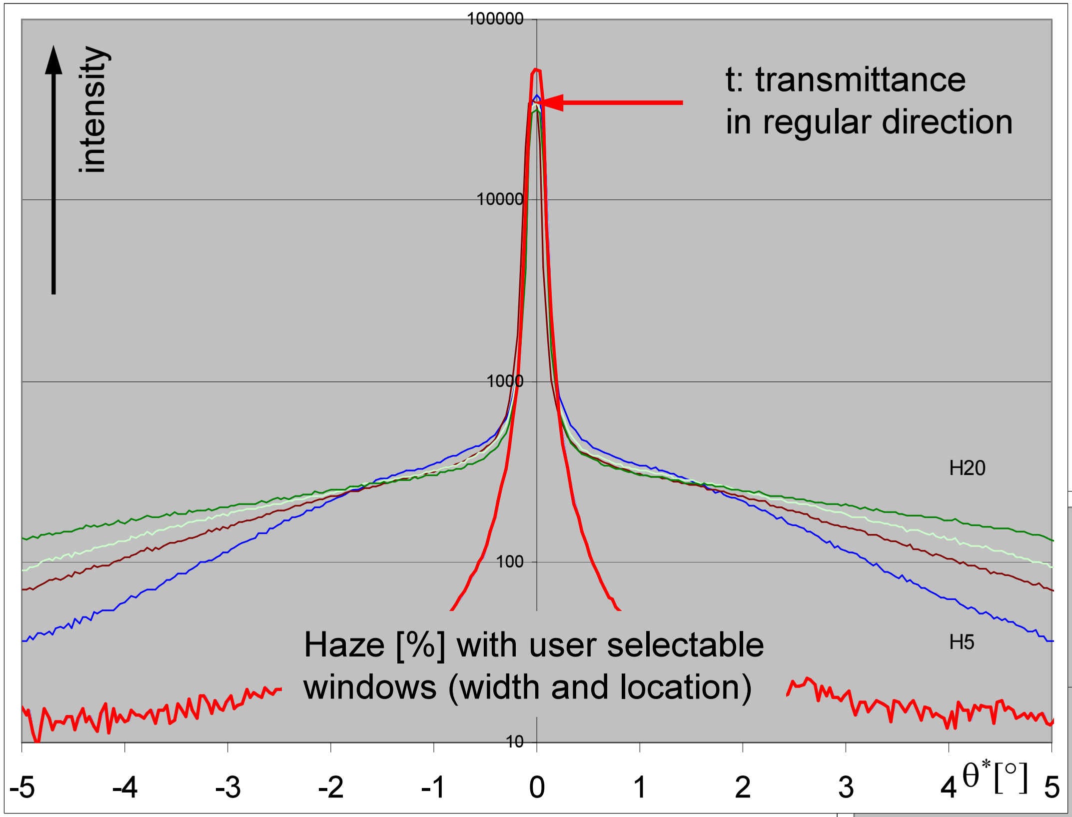
Specification of Scatter

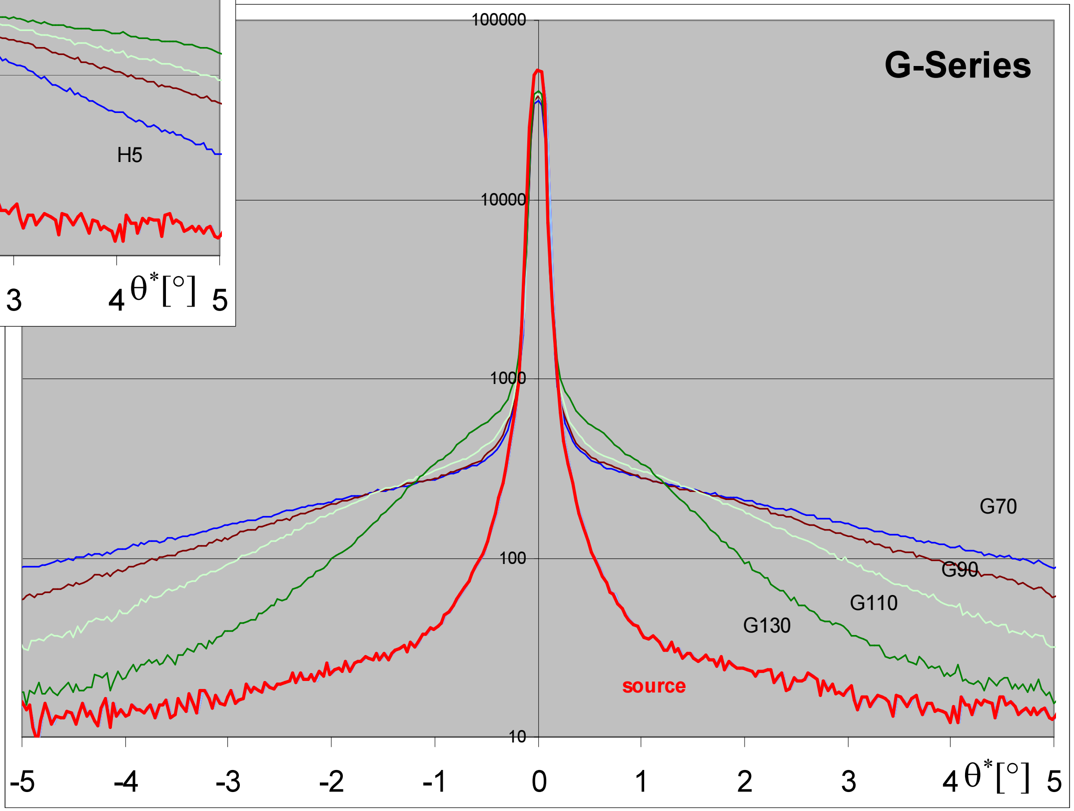


Specification of Scatter



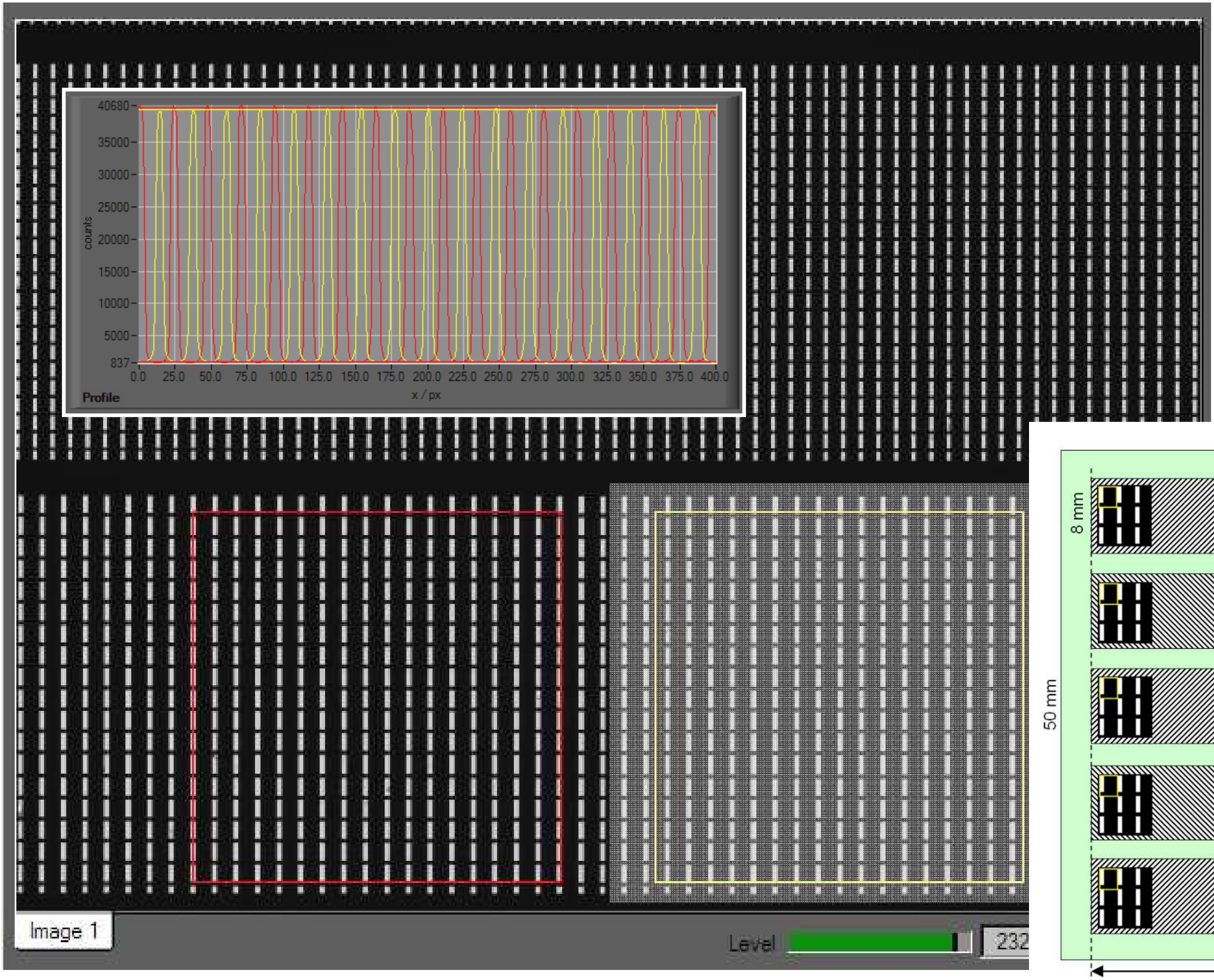
$$H(\alpha,\delta)=\frac{I\langle\alpha\rangle_{-\delta}+I\langle\alpha\rangle_{+\delta}}{2\cdot I\langle\alpha\rangle_0}$$



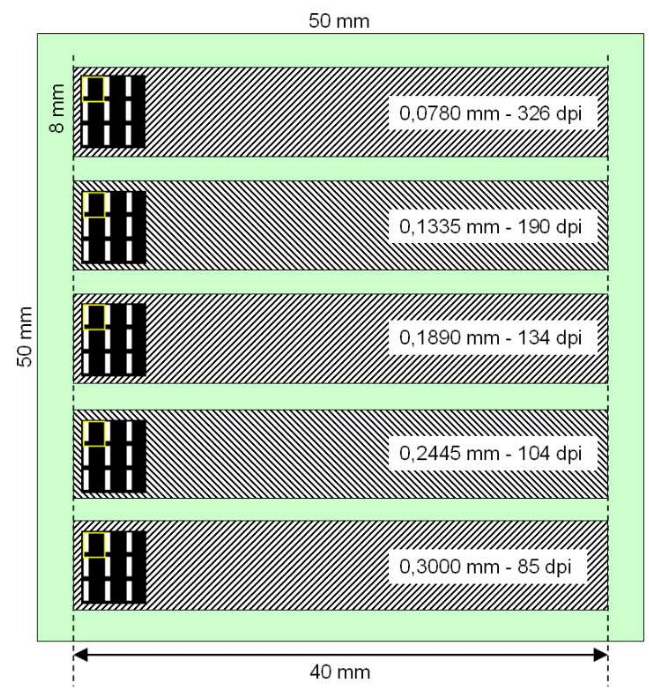


Transmittance distribution functions

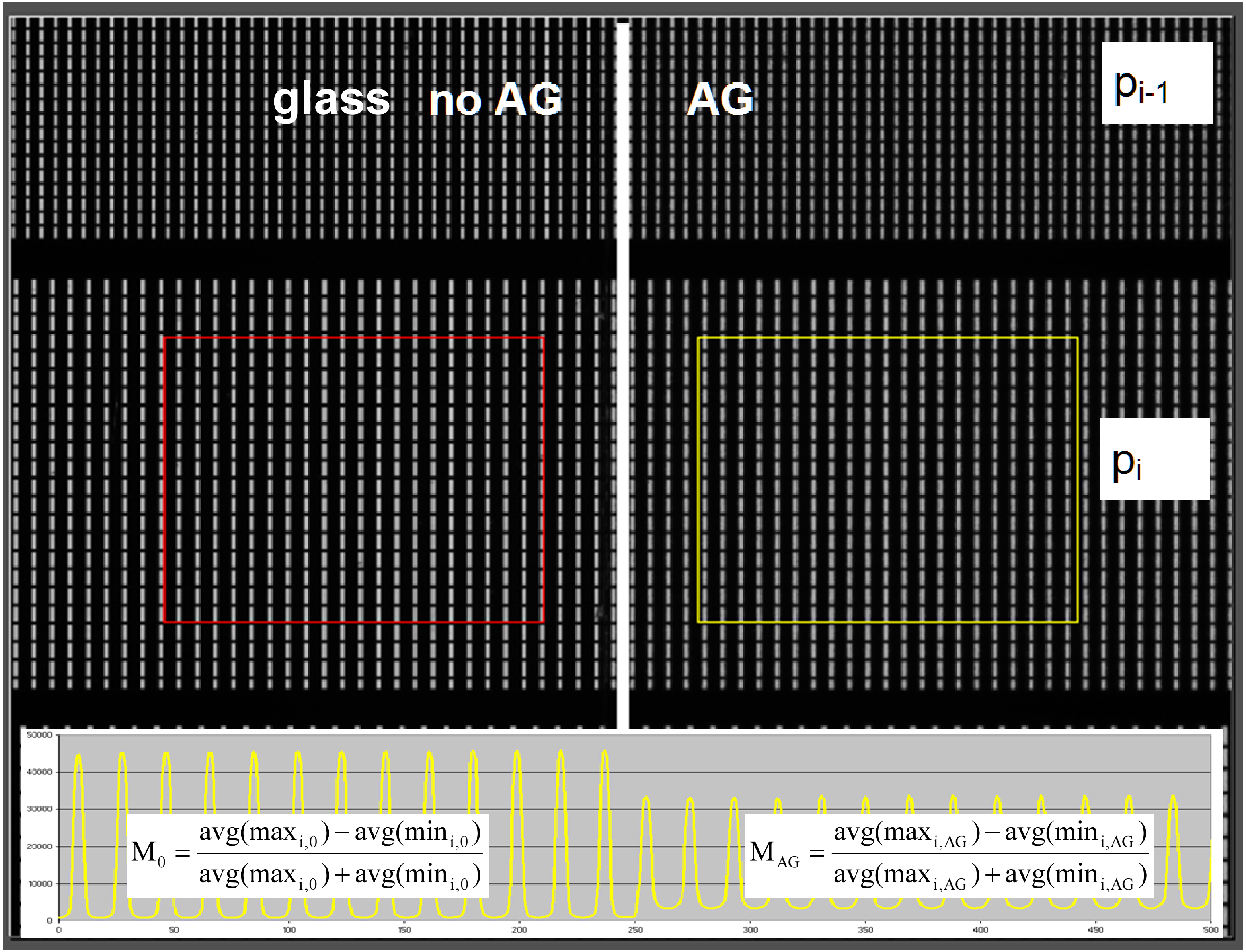
Fast evaluation of DOI-MT vs. pixel density



Support of routine evaluations in the laboratory



Distinctness of Image - Modulation Transfer

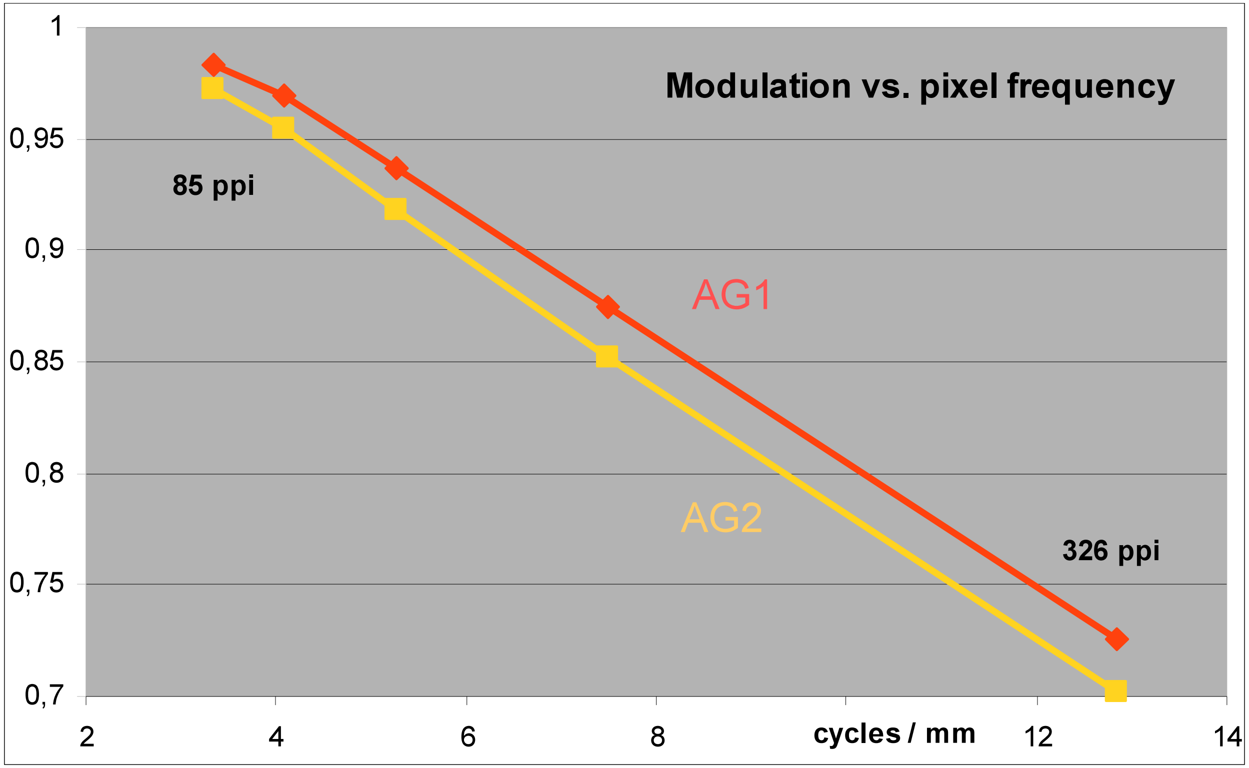


$$M_0 = \frac{avg(max_{i,0}) - avg(min_{i,0})}{avg(max_{i,0}) + avg(min_{i,0})}$$

$$M_{AG} = \frac{avg(max_{i,AG}) - avg(min_{i,AG})}{avg(max_{i,AG}) + avg(min_{i,AG})}$$

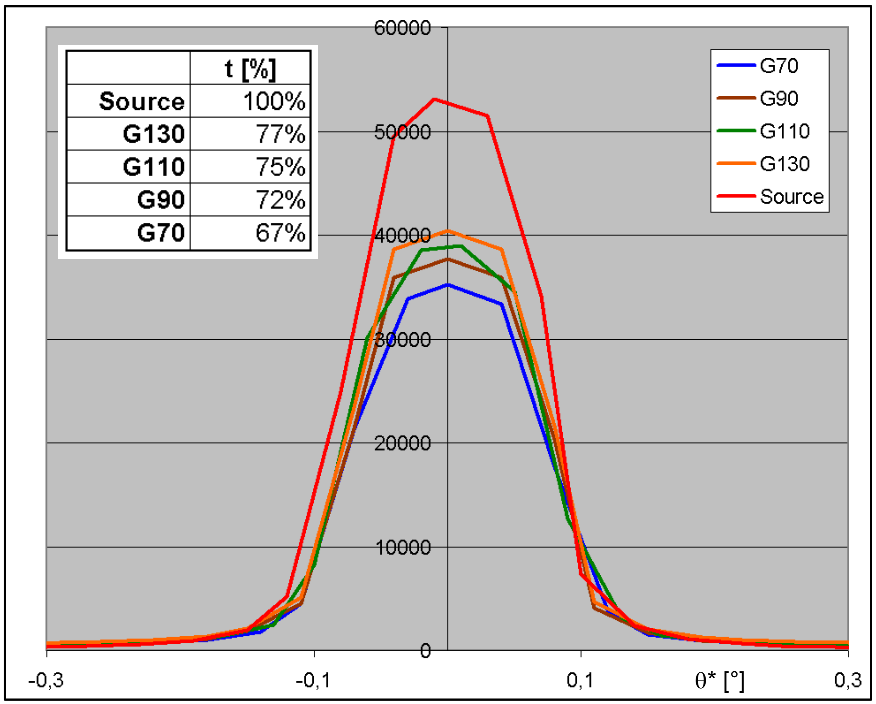
$DOI\text{-}MT = M_{AG} / M_0$

Modulation Transfer Function



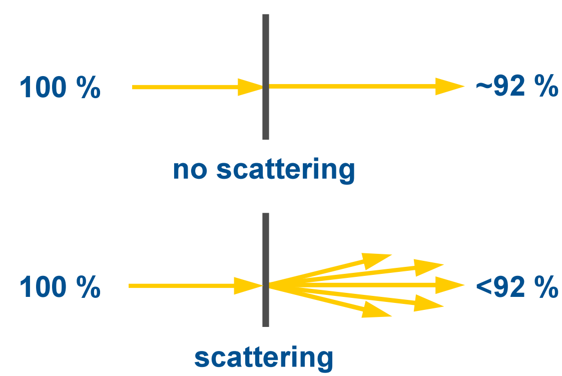
Modulation vs. pixel frequency (= 25.4 / pixel density [ppi]) for two low-scatter AG layers.

The transmittance in the regular direction, t, is a sensitive measure for the "clarity" of scattering samples.



Scattering distribution functions close the the regular direction (±0,3°)

Transmittance in the regular direction, t, of eight AG samples vs. gloss level as specified by the manufacturer



ASTM D1746 - 03 Standard Test Method for Transparency of Plastic Sheeting

A. C. Webber: "Method for the Measurement of Transparency of Sheet Materials", JOSA 47(1957)9, 785-789

What is Sparkle ?

Sparkle:

disturbing optical effect on direct view displays that are provided with scattering anti-glare (AG) layers.

M. E. Becker, J. Neumeier: Optical Characterization of Scattering AG-Layers, Proc. SID'11

Visual Perception of Sparkle

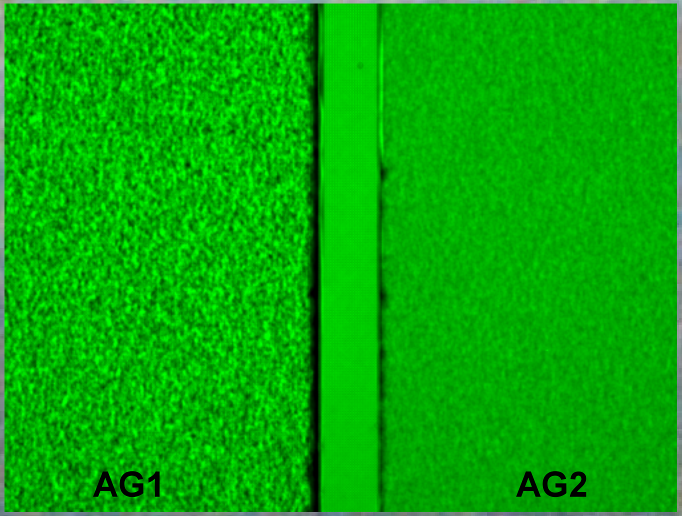
We do see:

statistic intensity (and chromaticity) modulations

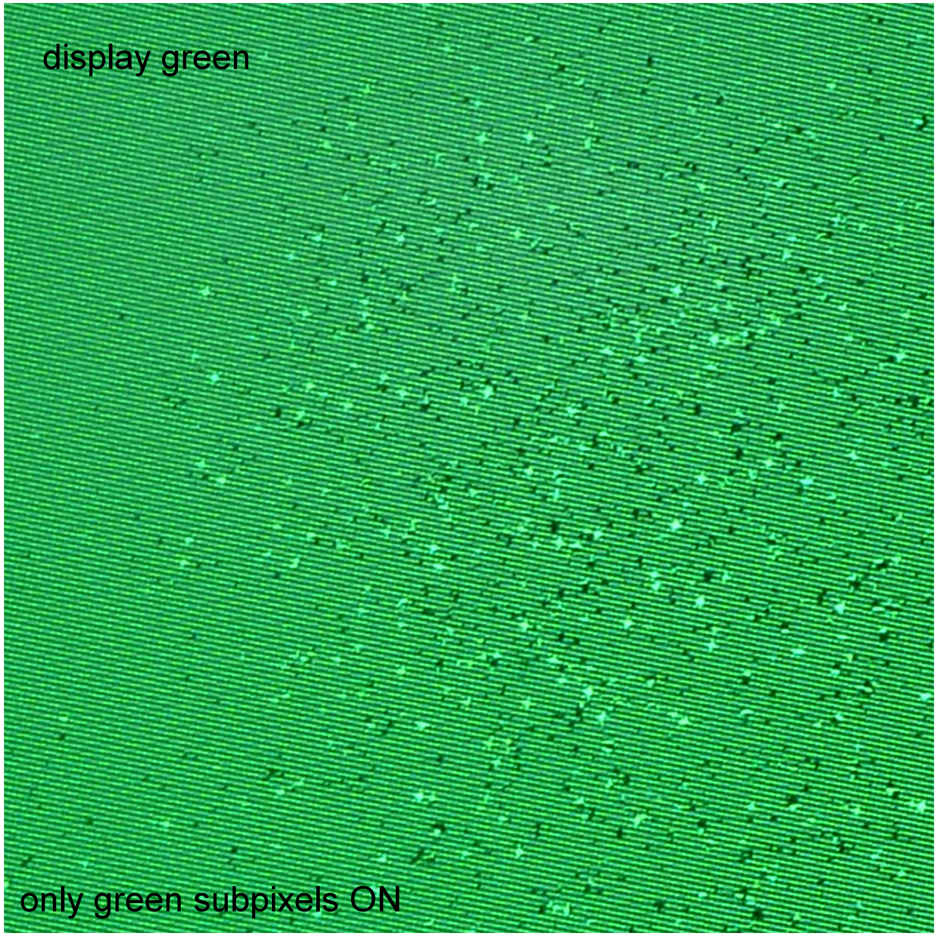
- vs. location on the display, and
- vs. direction of observation.

We do not see:

individual pixels of the display screen.

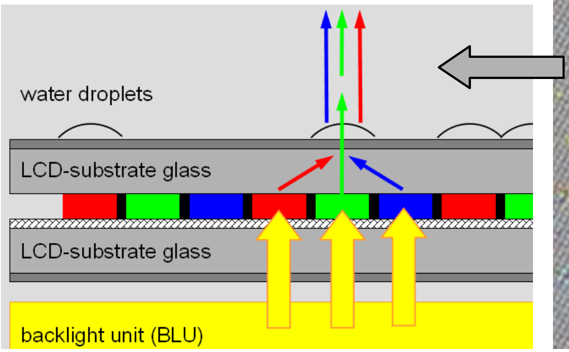


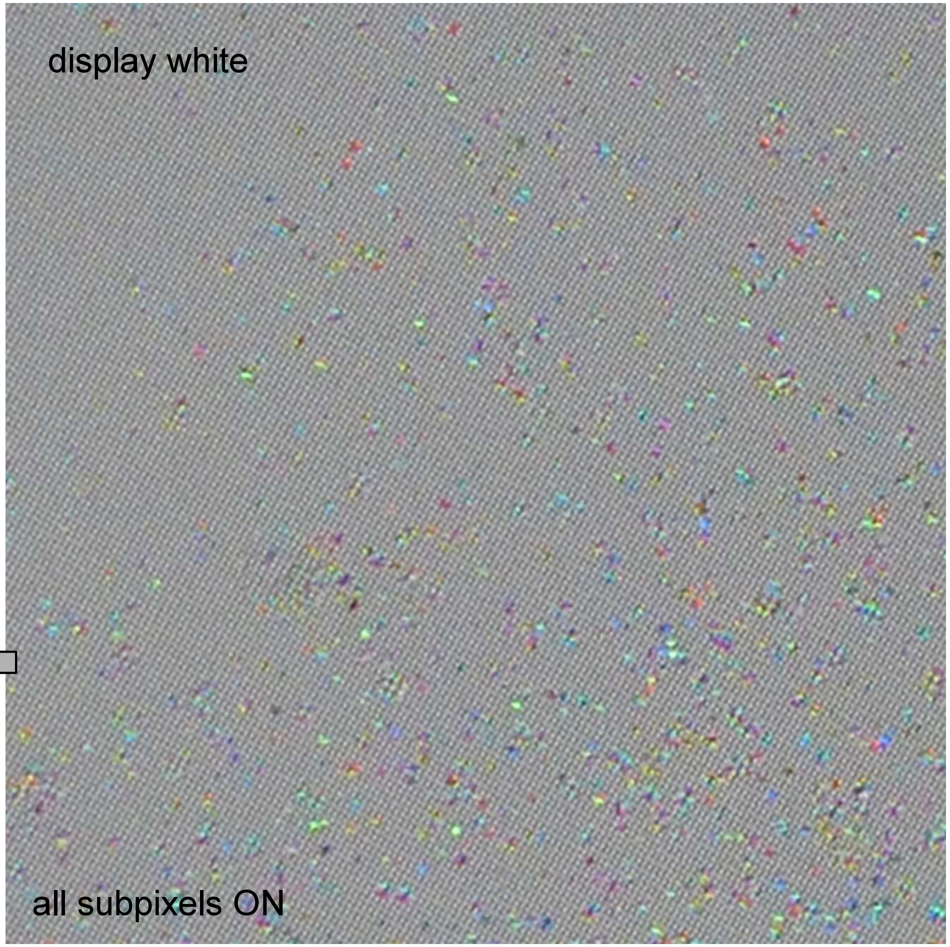
Sparkle is not restricted to one plane in space.



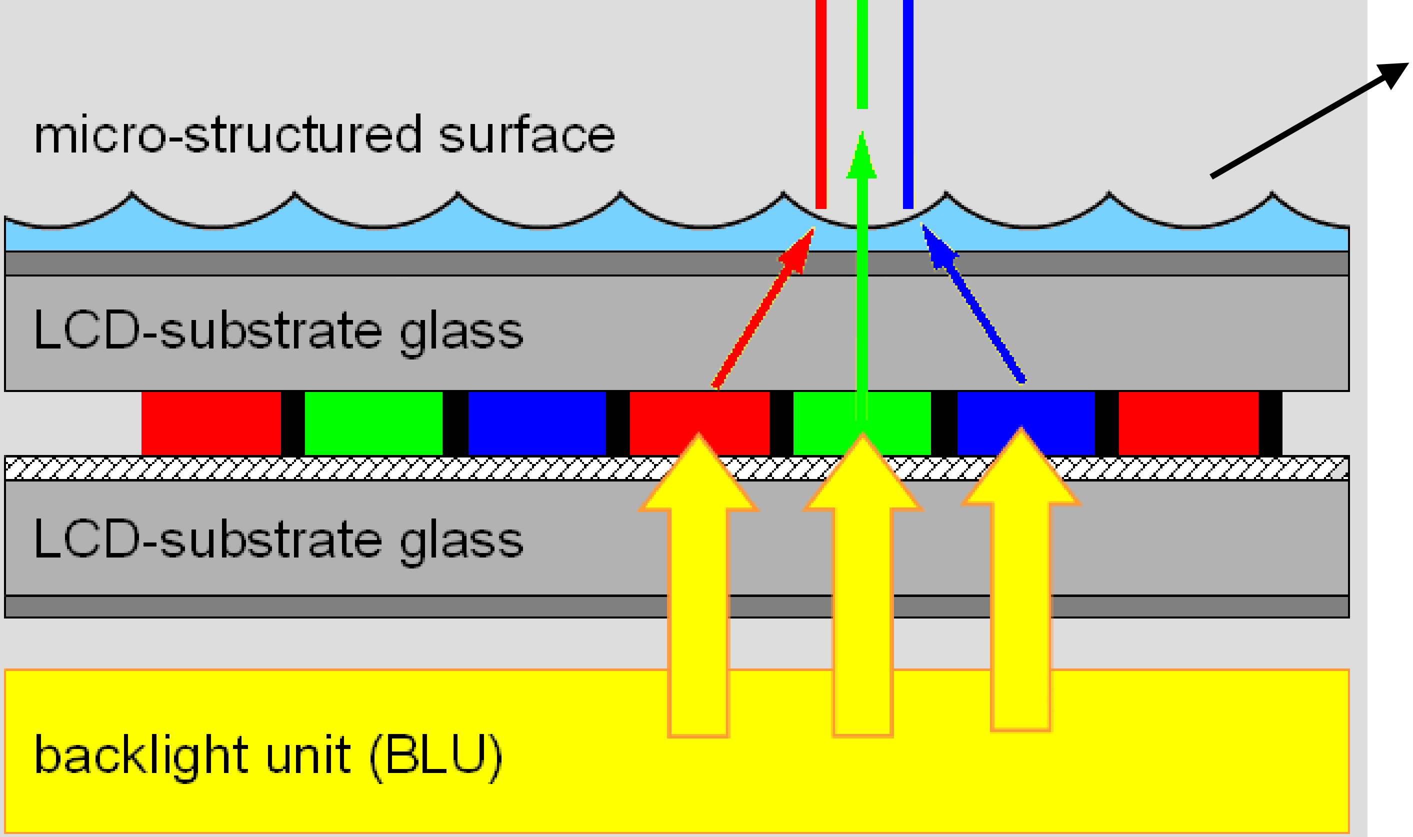
Water-droplets sprayed onto an LCD-monitor screen:
➲ formation of convex micro-lenses.

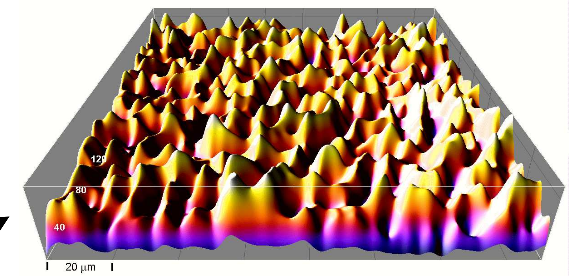
Refraction explains what we see.



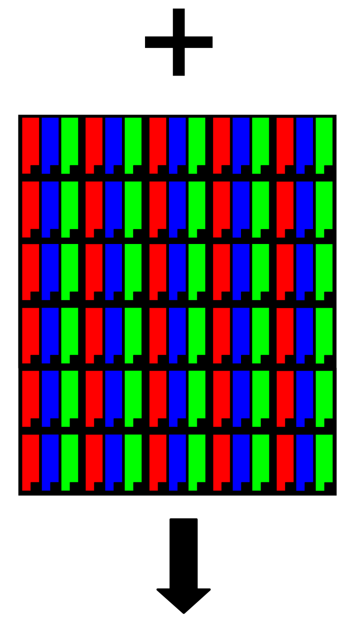


Sparkle: statistic intensity and chromaticity modulations
vs. location on the display and
vs. direction of observation.





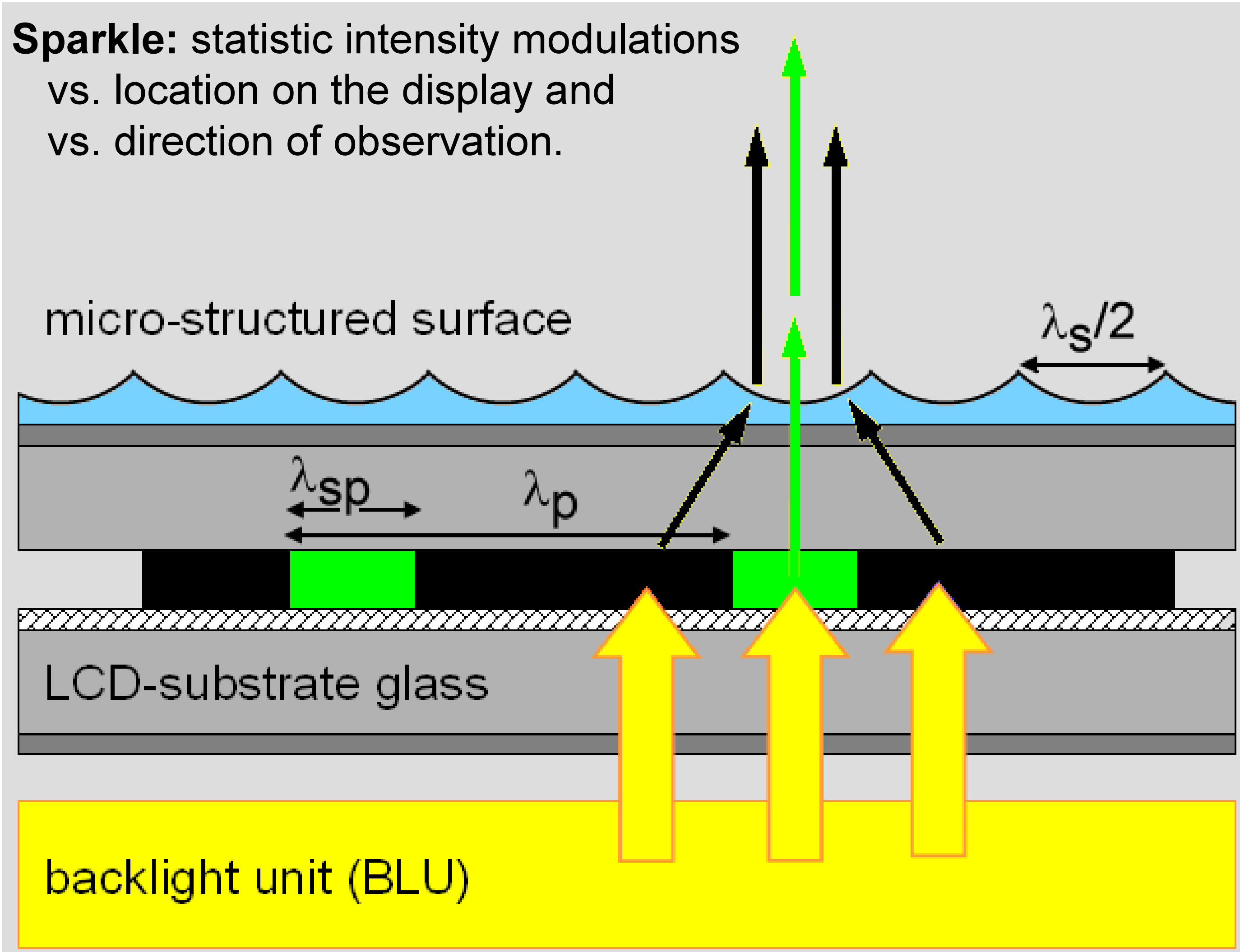
surface topography

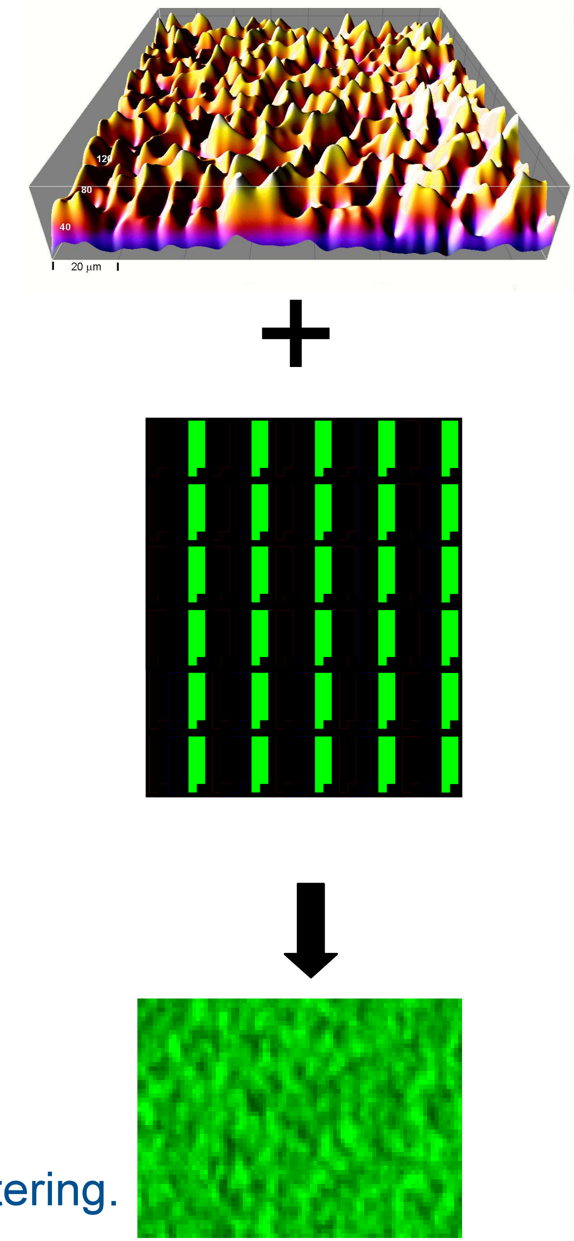


Generation of sparkle:

- Superposition of two structured layers,
- Modulation of transmitted light by **refraction**, diffraction and scattering.

Sparkle





Sparkle is distinctly visible with green illumination:

- Superposition of two structured layers,
- Modulation of transmitted light by **refraction**, diffraction and scattering.

Sparkle

85 ppi

104 ppi

134 ppi

190 ppi

326 ppi

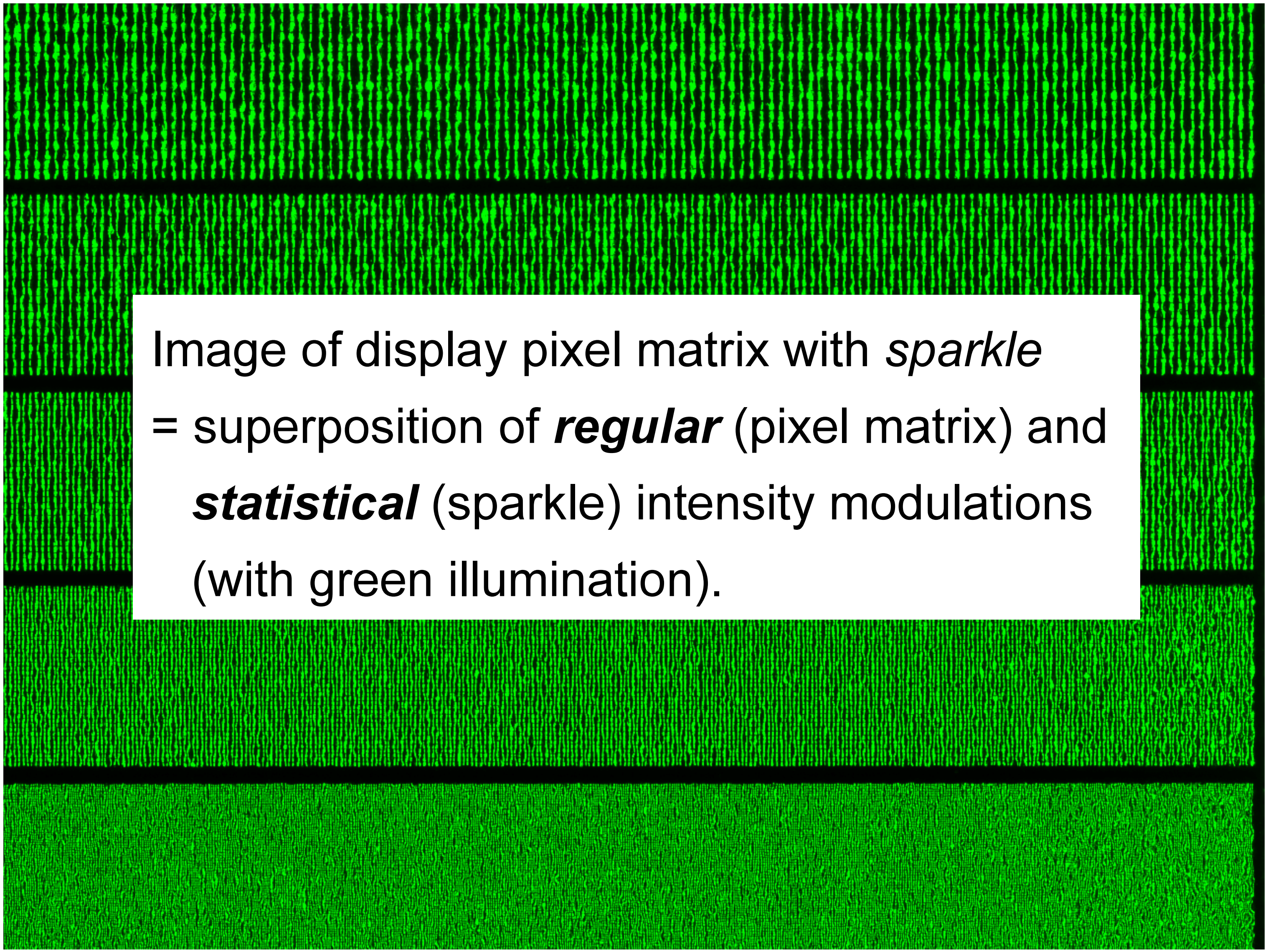
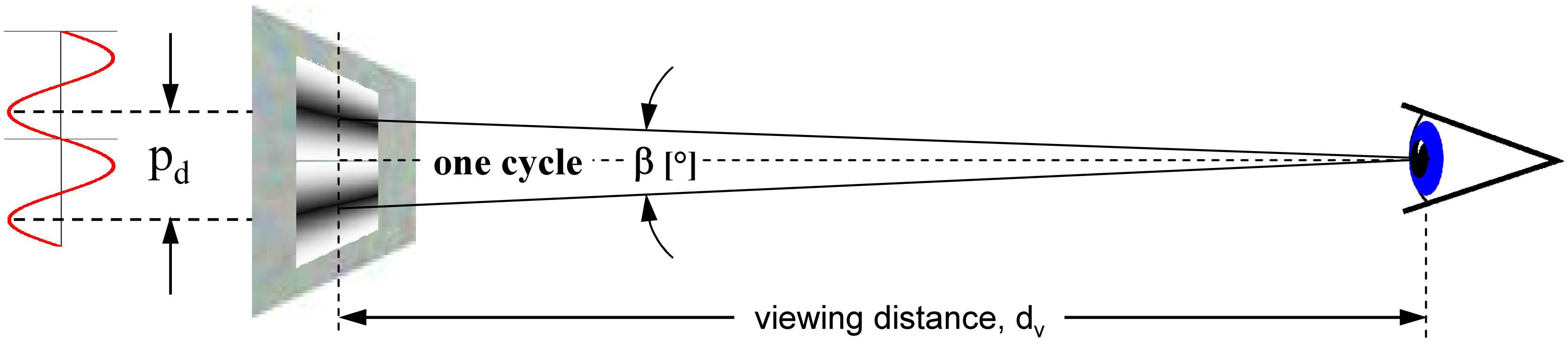


Image of display pixel matrix with *sparkle*
= superposition of ***regular*** (pixel matrix) and ***statistical*** (sparkle) intensity modulations (with green illumination).

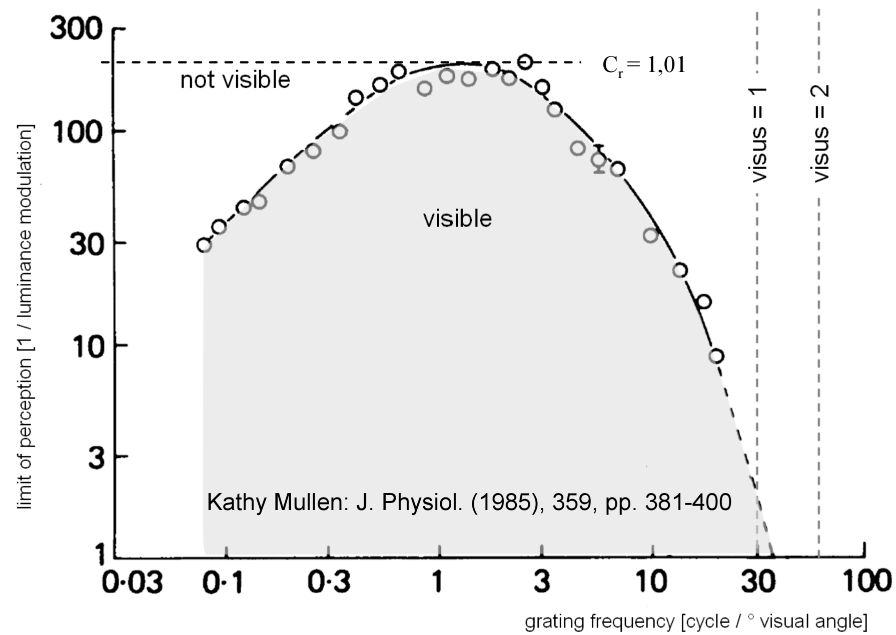


Observation condition

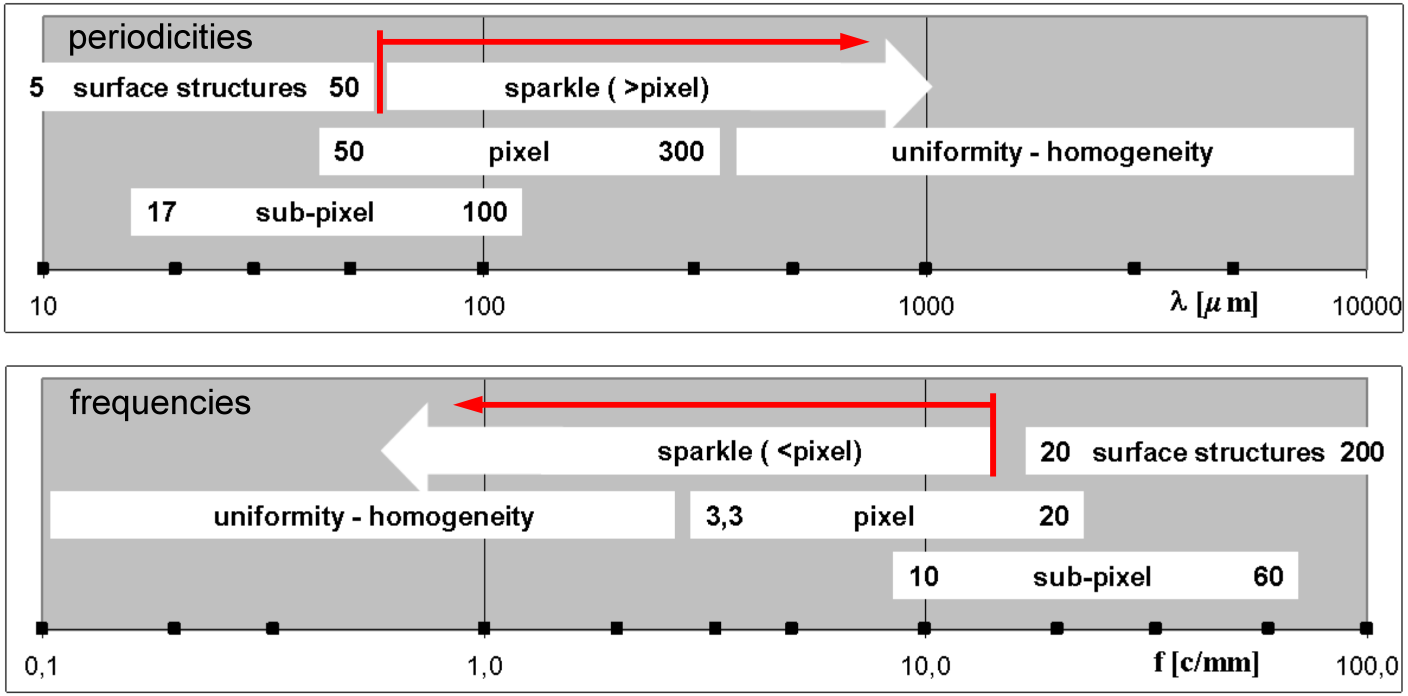
Adjustment of viewing distance

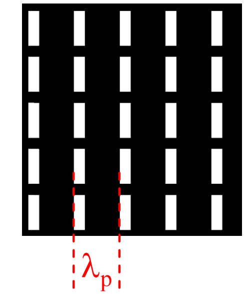
to make pixel pattern disappear while sparkle remains visible.

$$f_{vis,0}[cycles/°] = 1/\arctan(p_d/d_v)$$



Periodicities and Frequencies





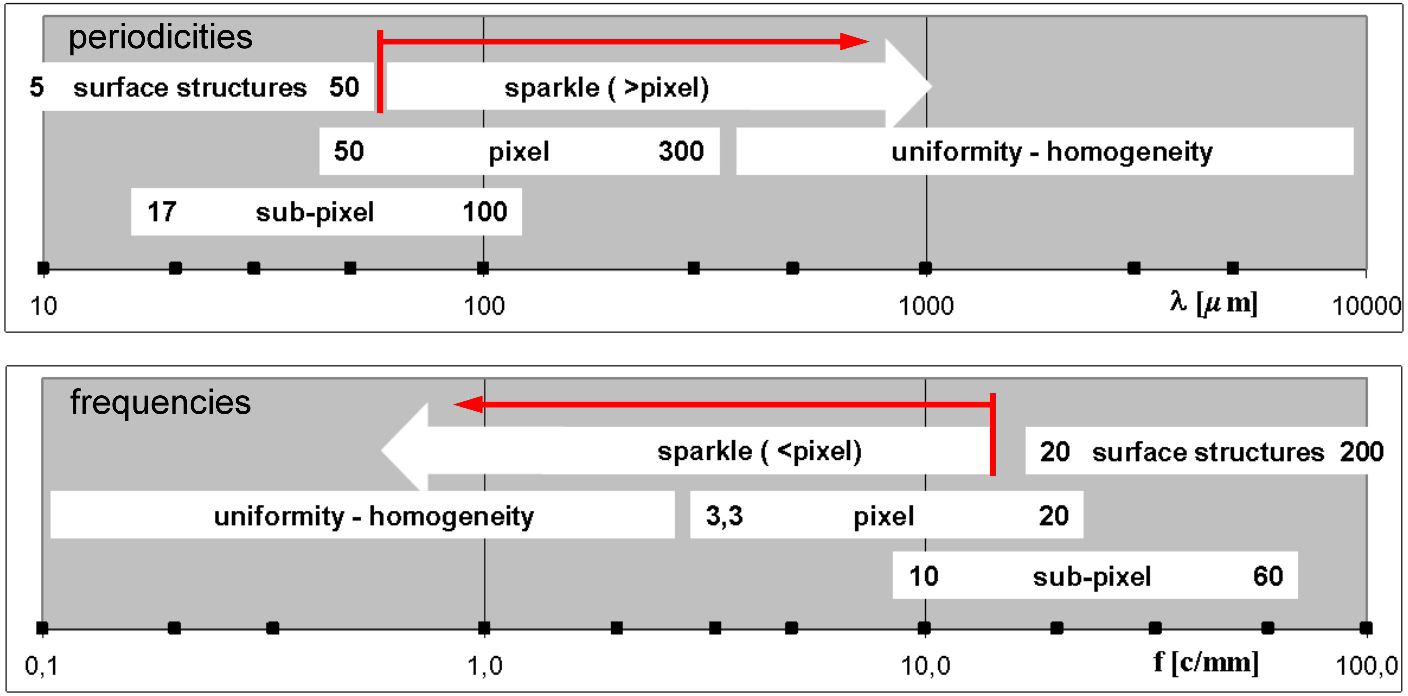
Display pixel matrix introduces **periodic intensity variations** while visual sparkle is caused by **statistic intensity modulations** (vs. location on the display and vs. direction of observation).

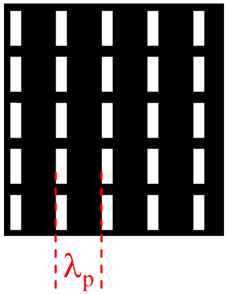
Display pixel dimensions range from 0,3 mm (PC desktop monitors for office work) to about 0,07 mm (high resolution display screens for handheld devices). Subpixel dimensions thus are in the range from 0,1 mm to 0,02 mm.

Sampling: >5 camera pixels (3.75 μm pixel pitch) per display pixel, up to 1:1 imaging.

Surface structures of AG-layer with average wavelengths in the range from 5 μm to 50 μm.

Periodicities and Frequencies





Separation of

- **periodic intensity variations**

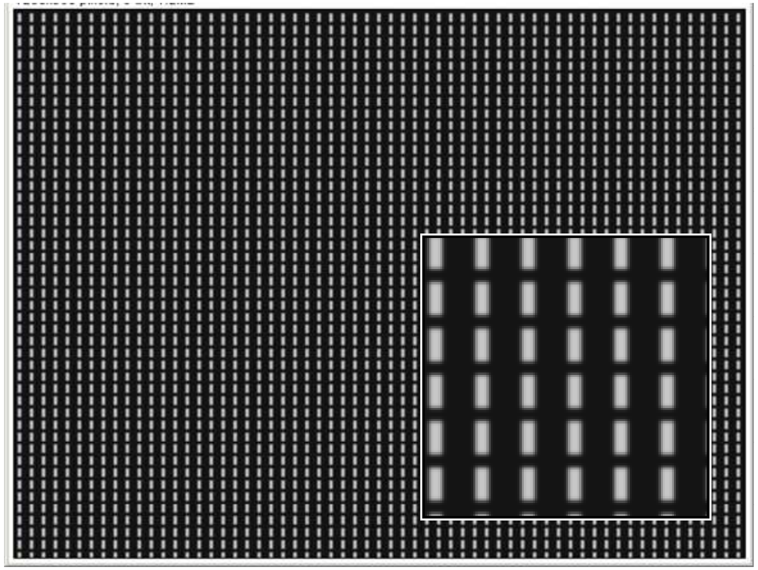
  from

- **statistic intensity modulations**

  in order to extract ***sparkle***

requires a **low-pass filter** for the spatial frequencies.

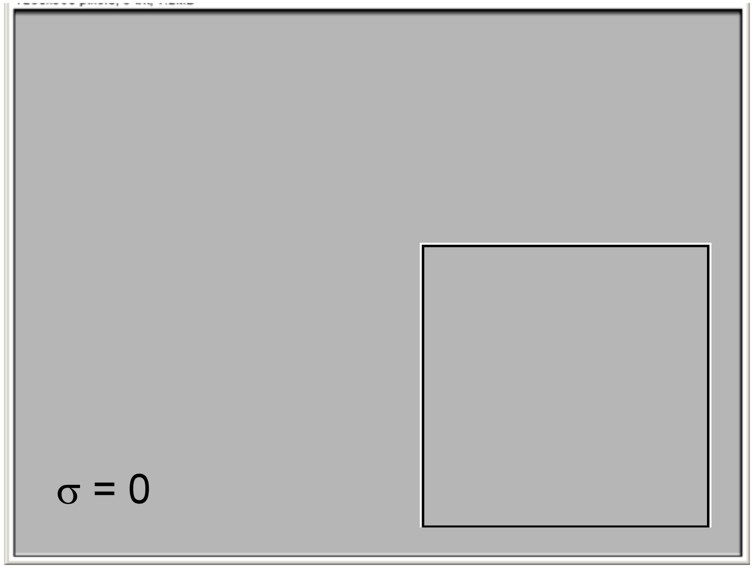
Spatial filtering (convolution) with rational kernel

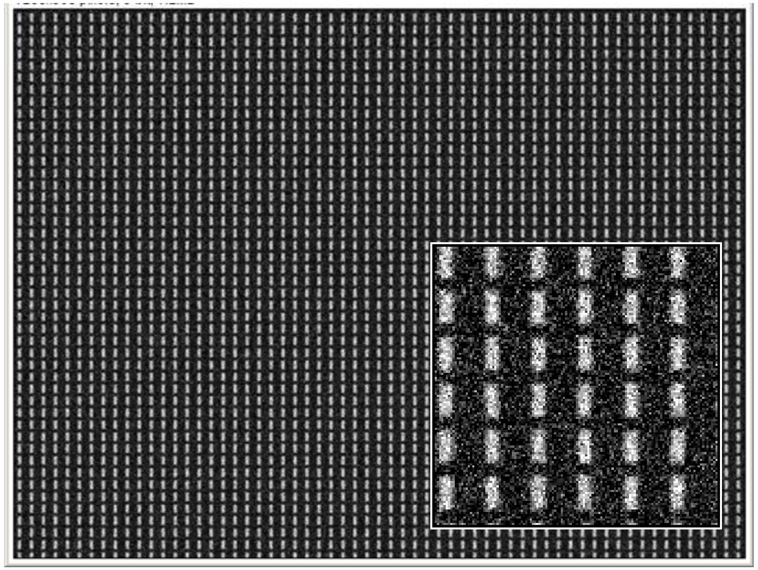


bare pixel matrix
without noise

filtering

Sparkle level =
σ / μ

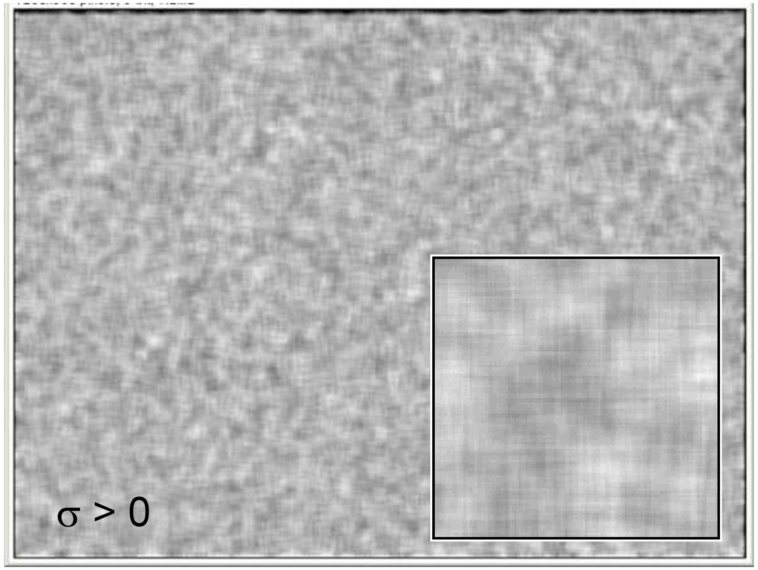




pixel matrix
with noise

filtering

Sparkle level =
σ / μ



Sparkle Evaluation

Single Image Method (SIM)

Record one image of
pixel matrix with AG-layer,

➲ **evaluate pixel ratio** (>5).

Apply spatial filtering to remove periodic modulations caused by the pixel matrix of the display.y

Sparkle level = σ / m

Difference Image Method (DIM)

Record first image of
pixel matrix with AG-layer,

➲ evaluate pixel ratio (>5).

Shift AG-layer (some mm).

Record second image
of pixel matrix with AG-layer.

Calculate *difference image*

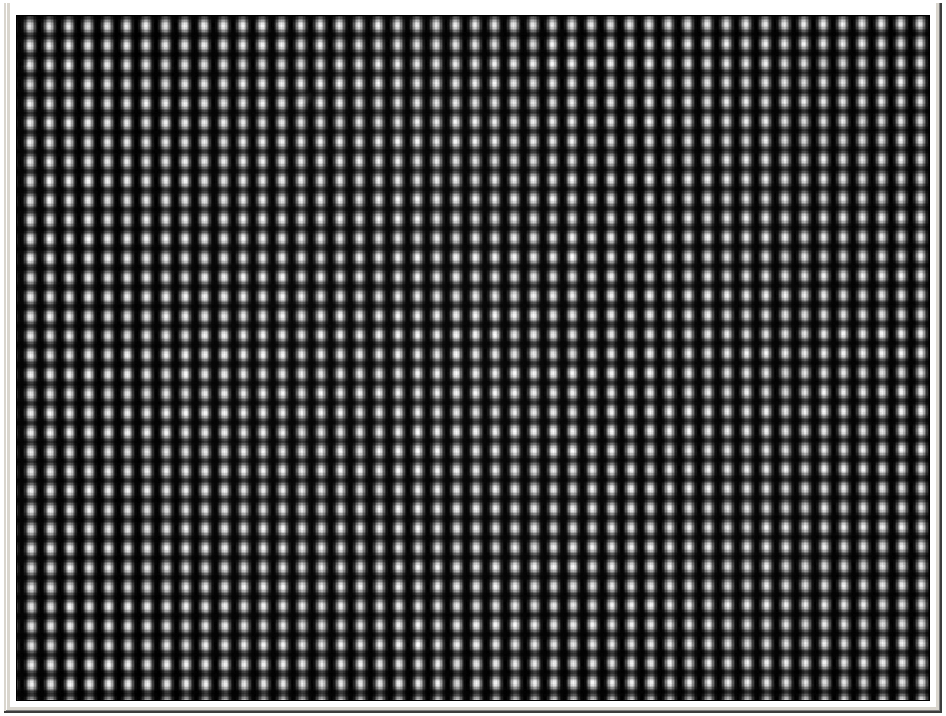
Apply spatial filtering to remove periodic modulations caused by the pixel matrix of the display.

Sparkle level = σ / m

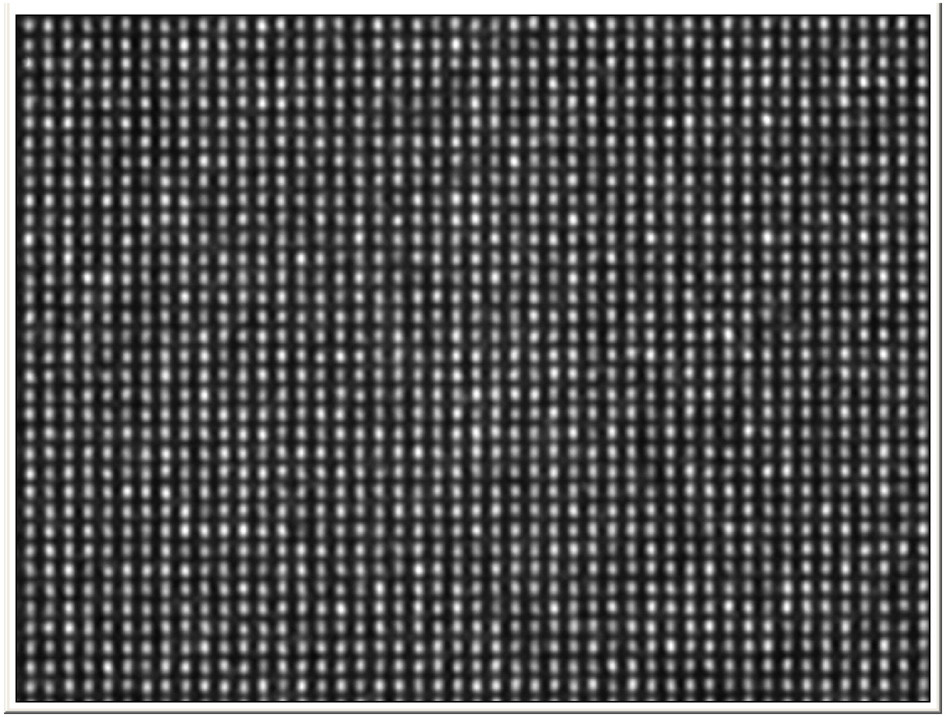
Evaluate

Evaluate

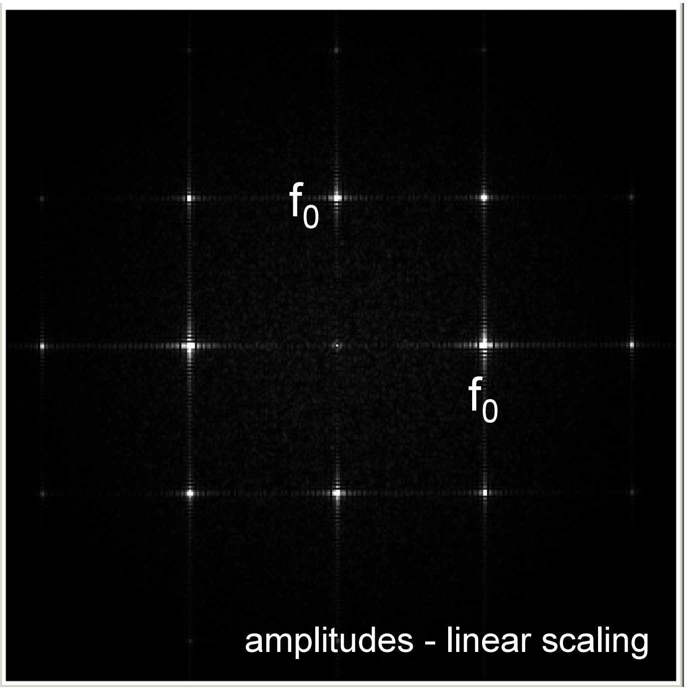
Sparkle in the Spatial Domain



Pixel matrix of tablet computer, green subpixels only.
Pixel pitch = 0.1 mm



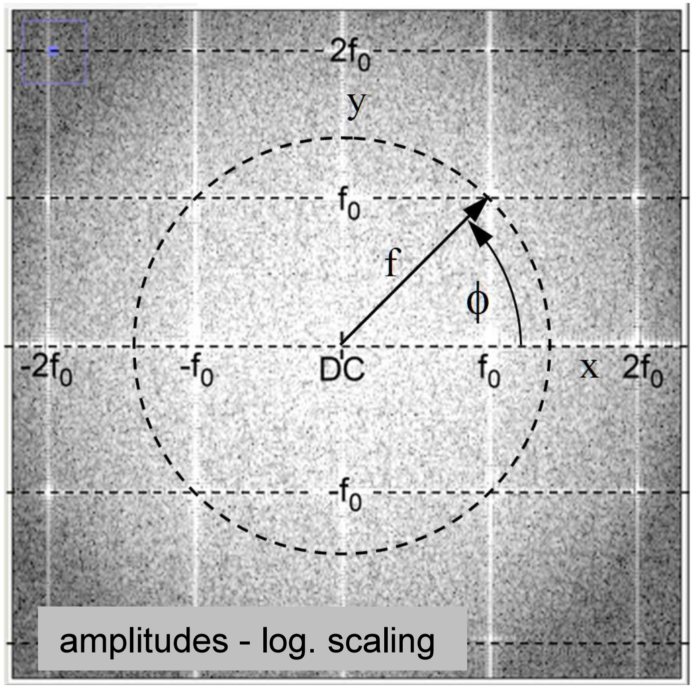
Pixel matrix of tablet computer, green subpixels only with low-sparkle AG-layer.



Result of 2D Fourier transformation of an image of the pixel matrix without AG-layer, Fourier amplitudes (indicated by grey levels with *linear scaling*) vs. spatial frequencies in x and y-direction with same scaling of frequency axes as below.

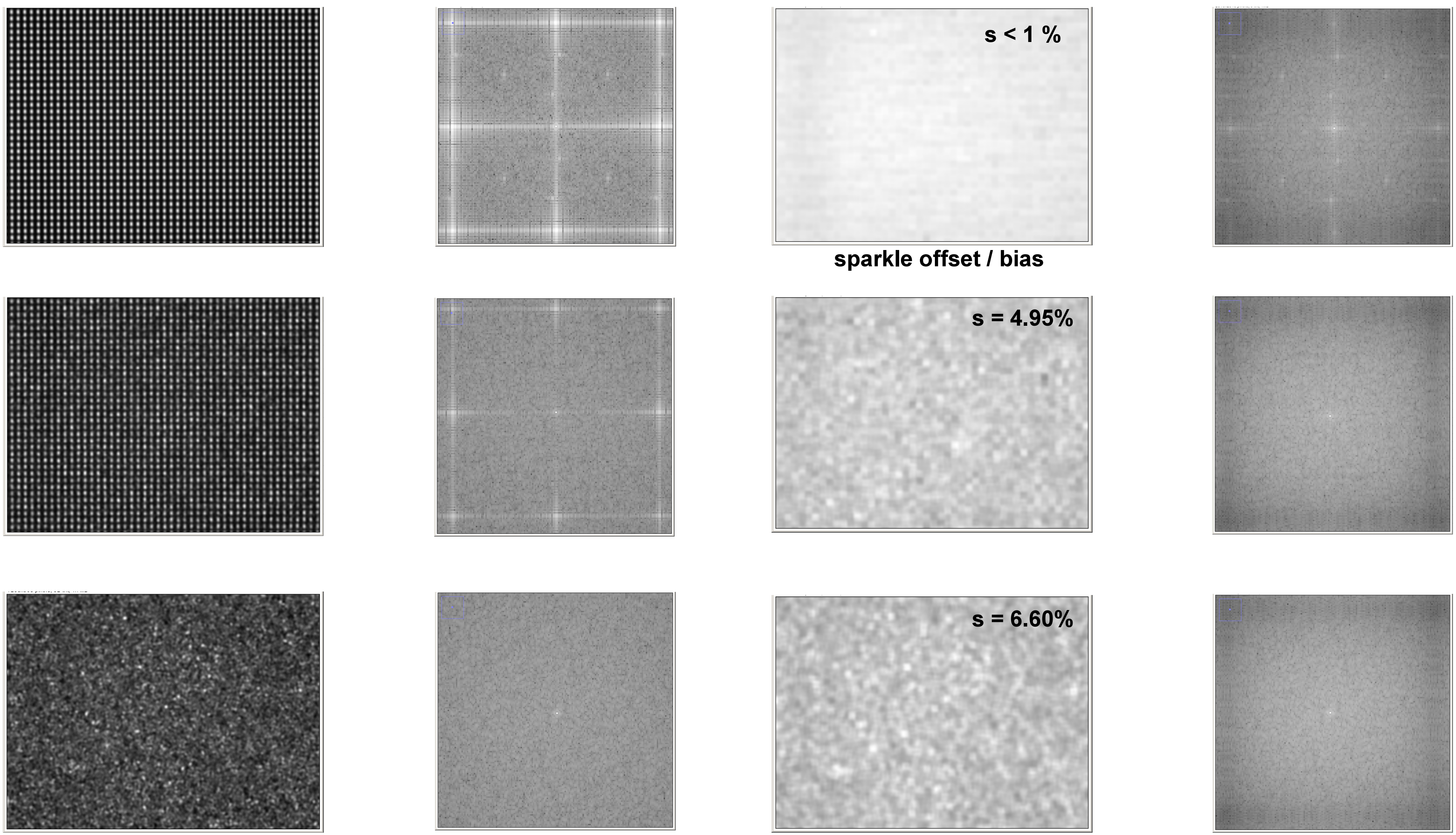
Result of 2D Fourier transformation of an image of a display *with a low sparkle AG-layer*, Fourier amplitudes (indicated by grey levels with *logarithmic scaling*) vs. spatial frequencies in x and y-direction. The length of the arrow represents the spatial frequency at the corresponding azimuth angle, ϕ.

f_0 is the fundamental frequency of the display pixel matrix.

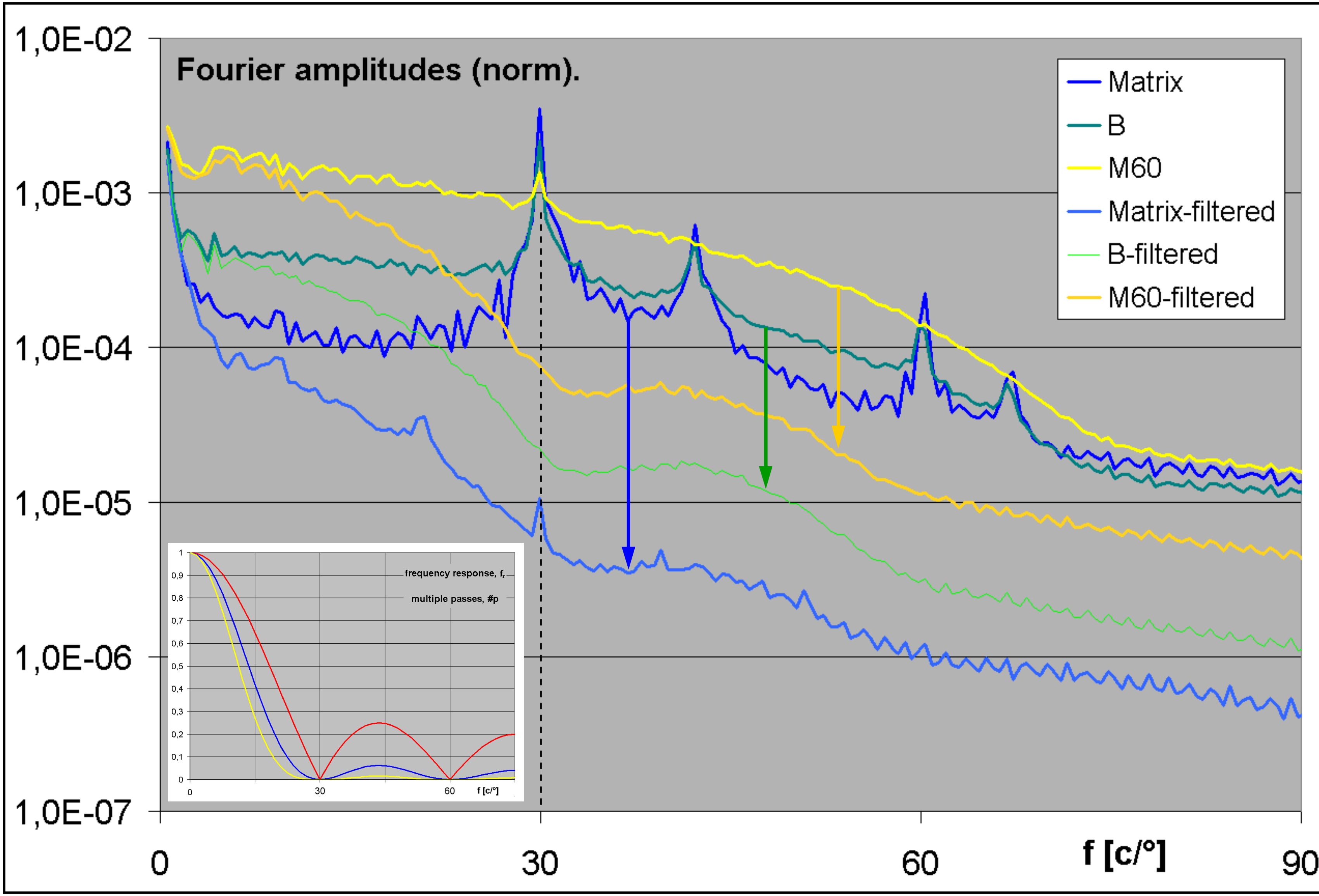


Sparkle in the Frequency Domain

Image | 2DFT | Filtered Image | 2DFT



Effect of Filtering in the Frequency Domain



Sparkle Evaluation

R. Adler, et al.: US Patent 4 972 117, 1990 sparkle = "random moiré"

D. R. Cairns, P. Evans: "Laser Speckle of Textured Surfaces: Towards High Performance Anti-Glare Surfaces", Proc. SID2007 ***laser speckle***

D. K. P. Huckaby, D. R. Cairns: "Quantifying "Sparkle" of Anti-Glare Surfaces", Proc. SID2009 ***laser speckle***

- M. E. Becker, J. Neumeier: "Optical Characterization of Scattering Anti-Glare Layers", Proc SID2011
- J. Gollier, et al.: "Display Sparkle Measurement and Human Response", Proc. SID2013
- T.-W. Hsu, et al.: "Novel Evaluation Method of Sparkle for LCDs with Different Anti-Glare Films", Proc IDW2014
- M. E. Becker: JSID 2015, Proc. SID2016

Sparkle Evaluation

M. E. Becker, J. Neumeier: "Optical Characterization of Scattering Anti-Glare Layers", Proc SID2011

Spatial filtering with rational kernel matched to display pixel matrix.

J. Gollier, et al.: "Display Sparkle Measurement and Human Response", Proc. SID2013

phase

Pixel power deviation (PPD): Boundaries between adjacent pixels are identified. Total intensity within each pixel is integrated and normalized by dividing by the pixel powers from the bare pixel matrix image. The standard deviation of the distribution of pixel powers is then calculated to give the PPDr value.

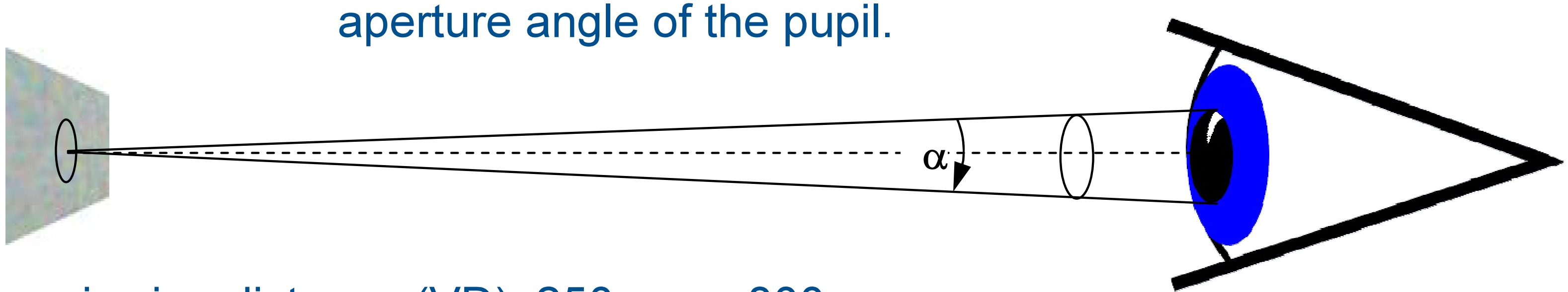
T.-W. Hsu, et al.: "Novel Evaluation Method of Sparkle for LCDs with Different Anti-Glare Films", Proc IDW2014

Summation of Fourier amplitudes.

➲ Spatial filtering with rational kernel (matched to display pixel matrix) offers highest sparkle sensitivity.

Effect of Lens Aperture

α: angle subtended by the pupil at the target,
aperture angle of the pupil.



viewing distance (VD): 250 mm - 800 mm

pupil diameter (PD):
3 mm to 9 mm depending
on the state of adaptation.

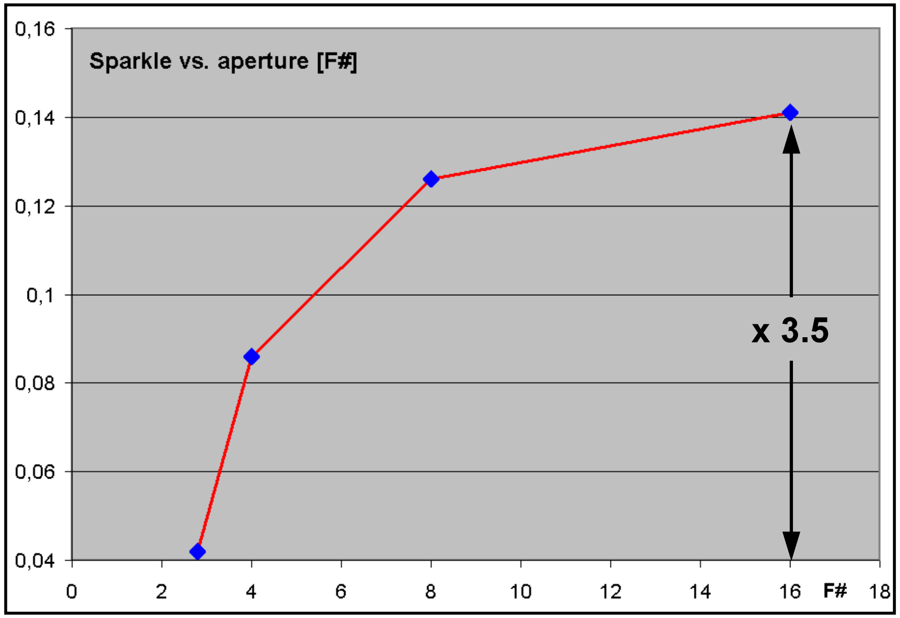
α_{min} : arctan (3 mm / 800 mm) = 0,22° (~13'),

α_{max} : arctan (9 mm / 250mm) = 2,06°.

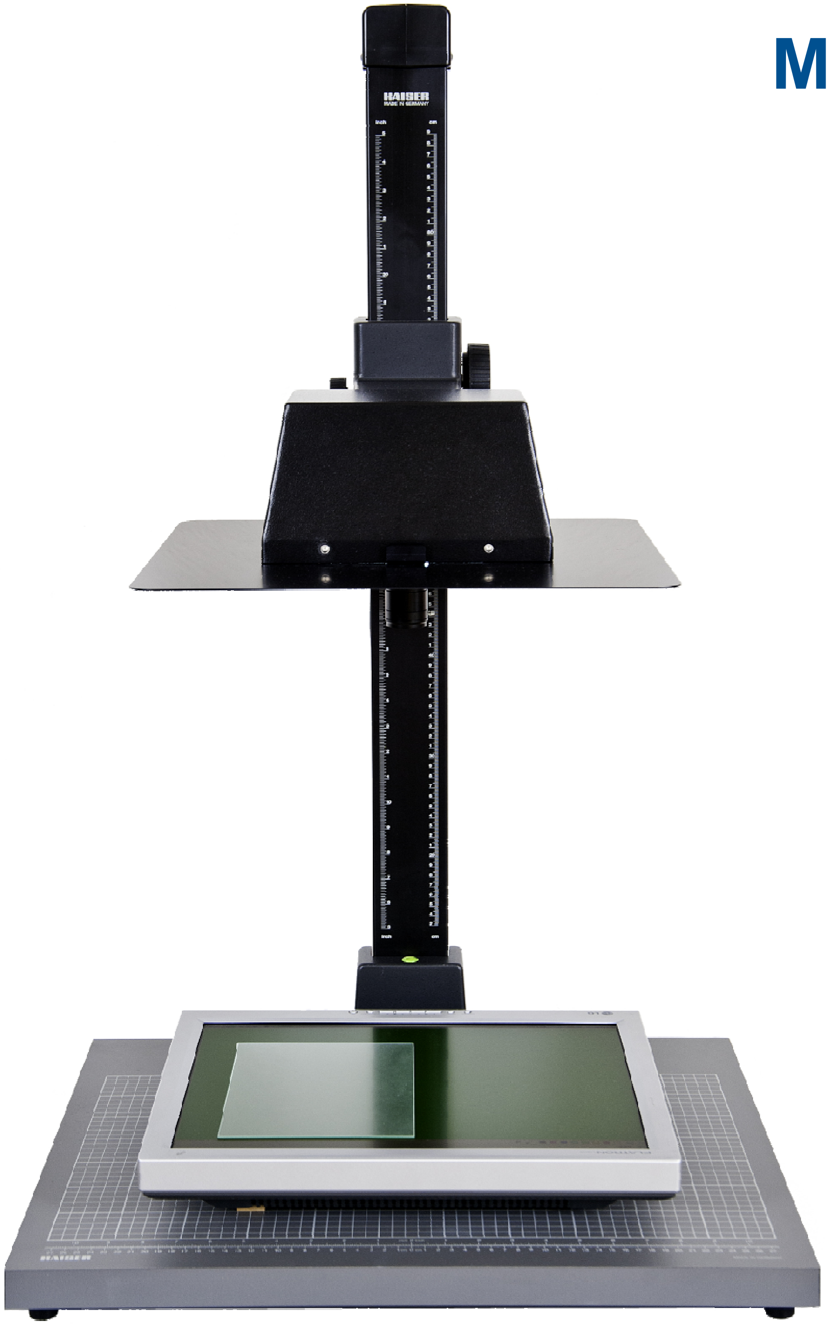
Larger aperture of objective lens averages out directional variations
➲ reduction of sparkle level.

Pronounced increase of sparkle level with F# (= f / D) can be measured.

Only measurements with the same aperture angle should be compared.



SMS-1000 Features



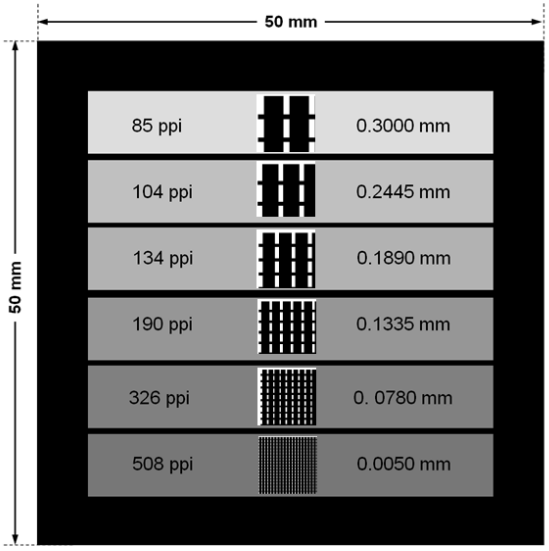
Measurement and Evaluation of

- Sparkle (2 methods)
- Distinctness of Image (MTF)
- Transmittance Distribution
- Reflectance Distribution
  - optional microscope head,
  - features continuously expanded.

Accessories

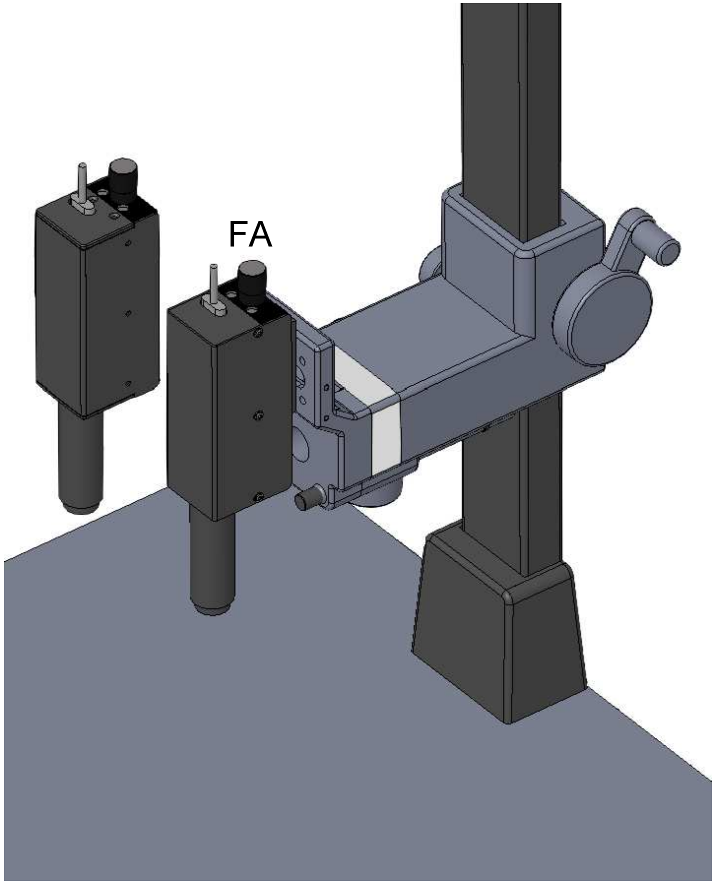
Microscope head

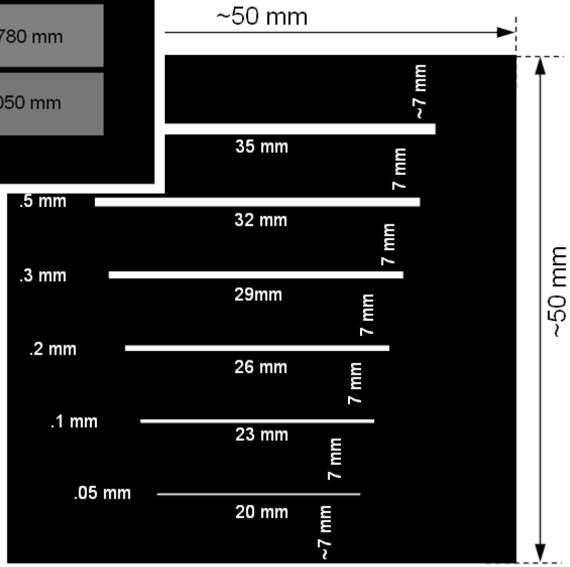
The optional microscope head is provided for detailed photometric analysis of small features, i. e. picture elements (pixels) and sub-pixels of display devices, for example, for evaluation of "pixel crosstalk". It comprises a translational stage with fine adjustment (FA), a photometric camera and a variety of objective lenses with an imaging ratio of 1:2 or 1:4.



Pixel pattern matrix

replacing actual displays

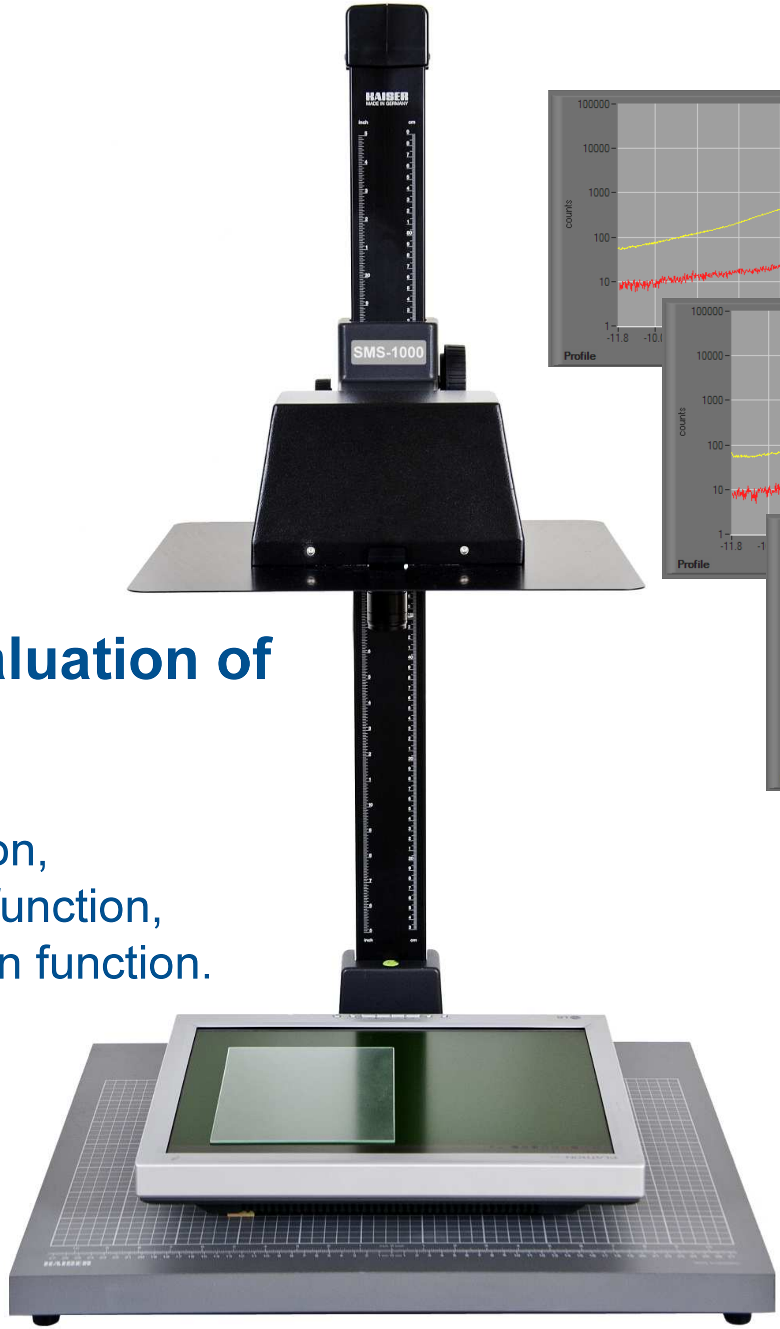


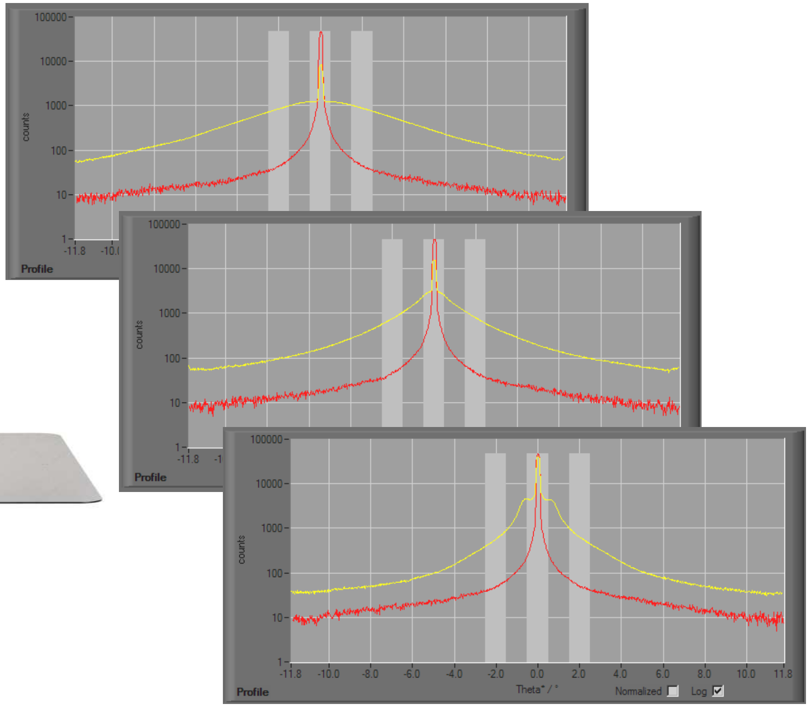


Slit mask

for transmissive illumination (line source)

DM&S
Sparkle Measurement System
SMS - 1000





Measurement & Evaluation of

- Sparkle,
- DOI (MTF) in transmission,
- Reflectance distribution function,
- Transmittance distribution function.