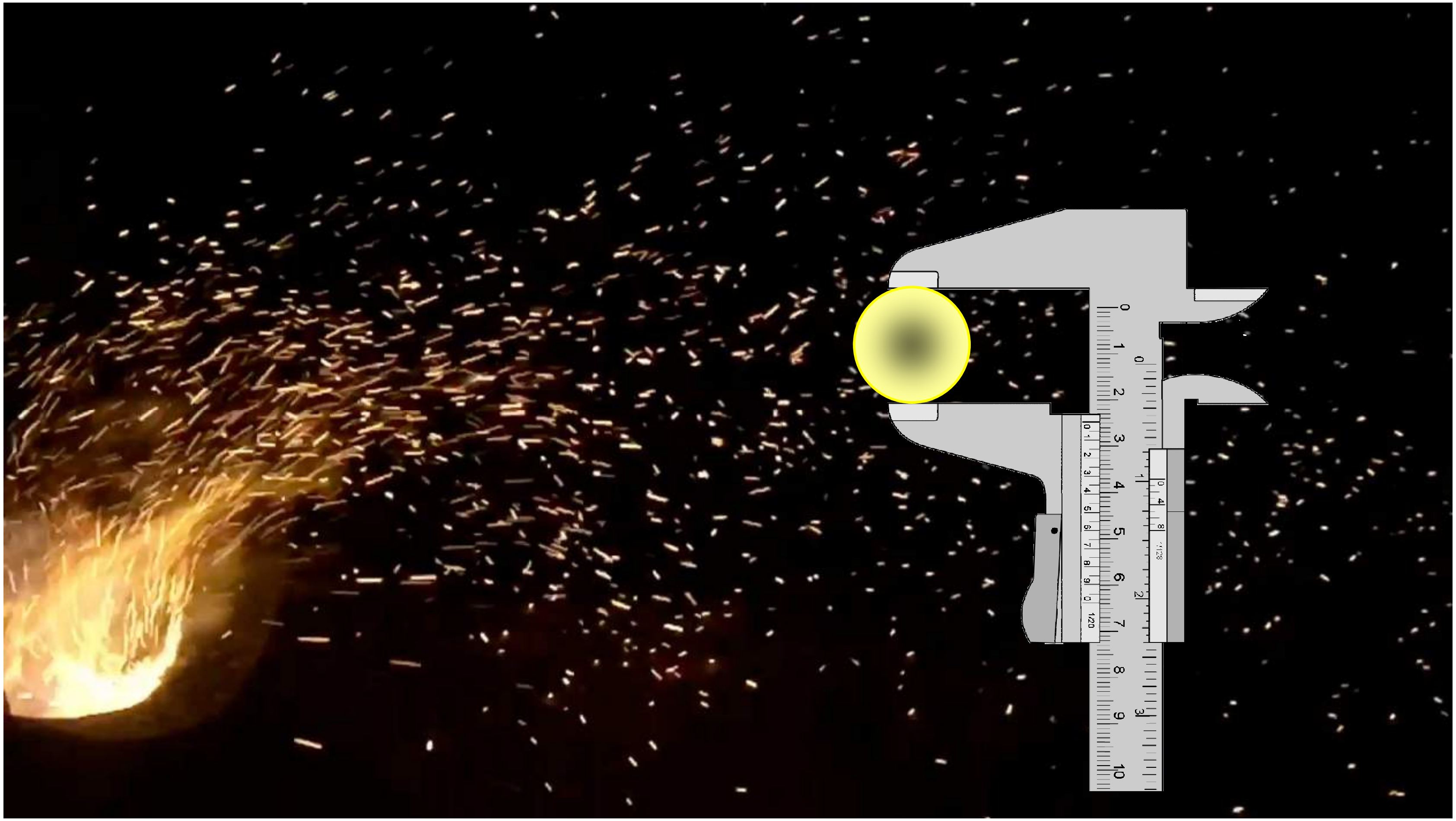
The measurement of sparkle and graininess

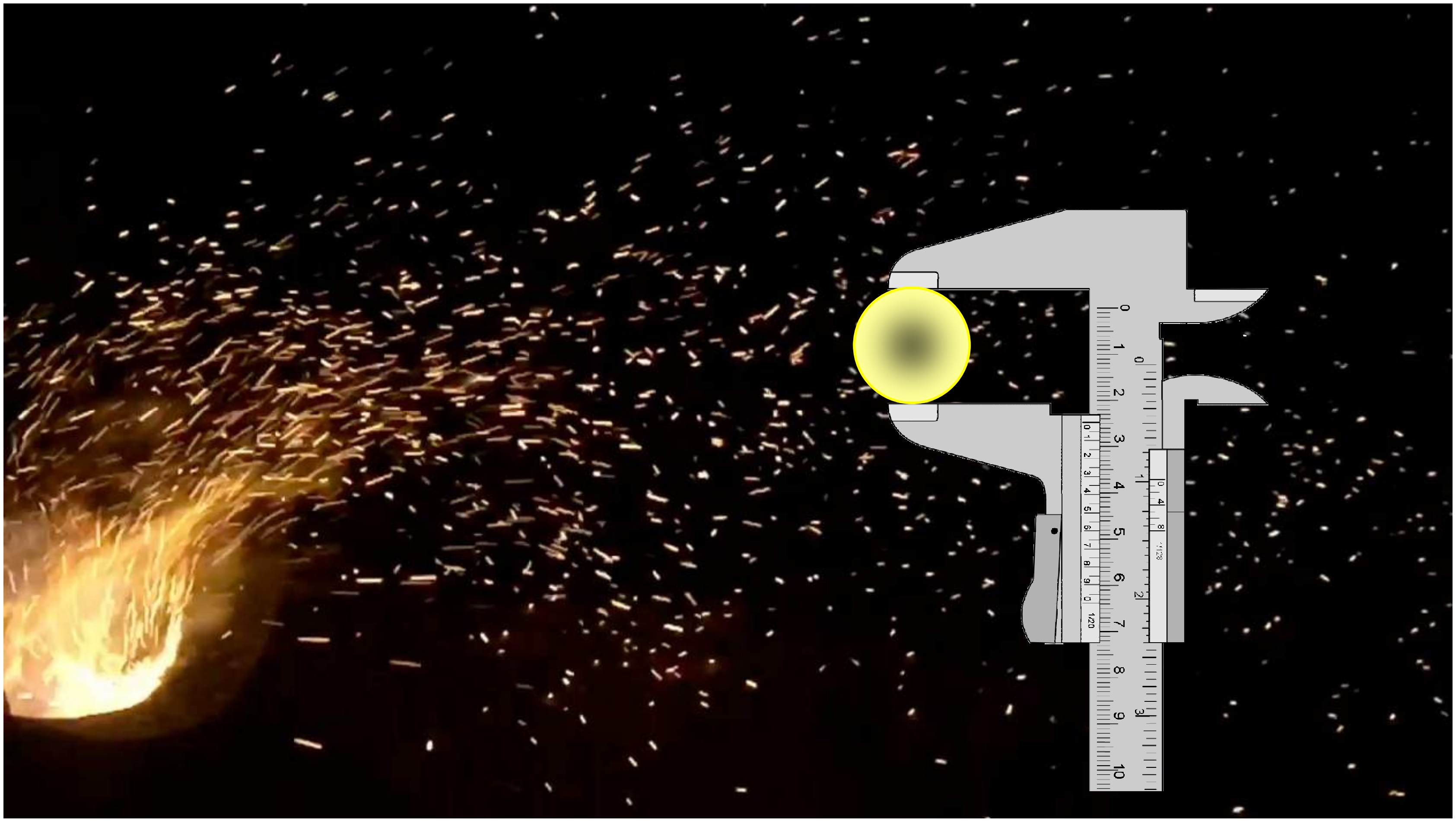
► Intended Sparkle vs. Unwanted Sparkle ◄



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

The measurement of sparkle and graininess

☺ ► Sparkle vs. Sparkle ◄ ☹



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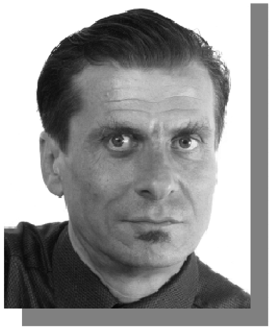
Michael E. Becker, Dr.-Ing. / PhD



- Electrical Engineering at Karlsruhe University,
- 1979 -1984: Teaching and research (LCD technology, metrology and modeling) at Karlsruhe University (KIT),
- Commercialization of display metrology and LCD modeling tools at **autronic**, Karlsruhe (1985-1993),
- MD/CTO at **autronic-Melchers** (1993-2001).

- **2002: Establishment of Display-Metrology & Systems**
- **since 2012: Scientific Advisor - Instruments Systems GmbH**

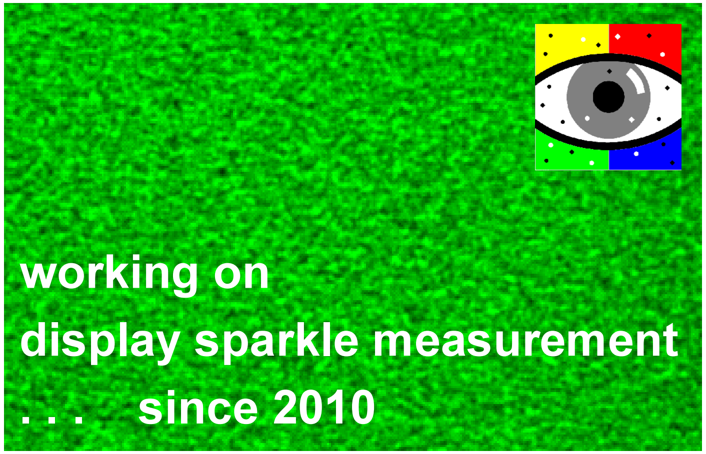
Instrument Systems
KONICA MINOLTA Group

Light and Display-Measurement

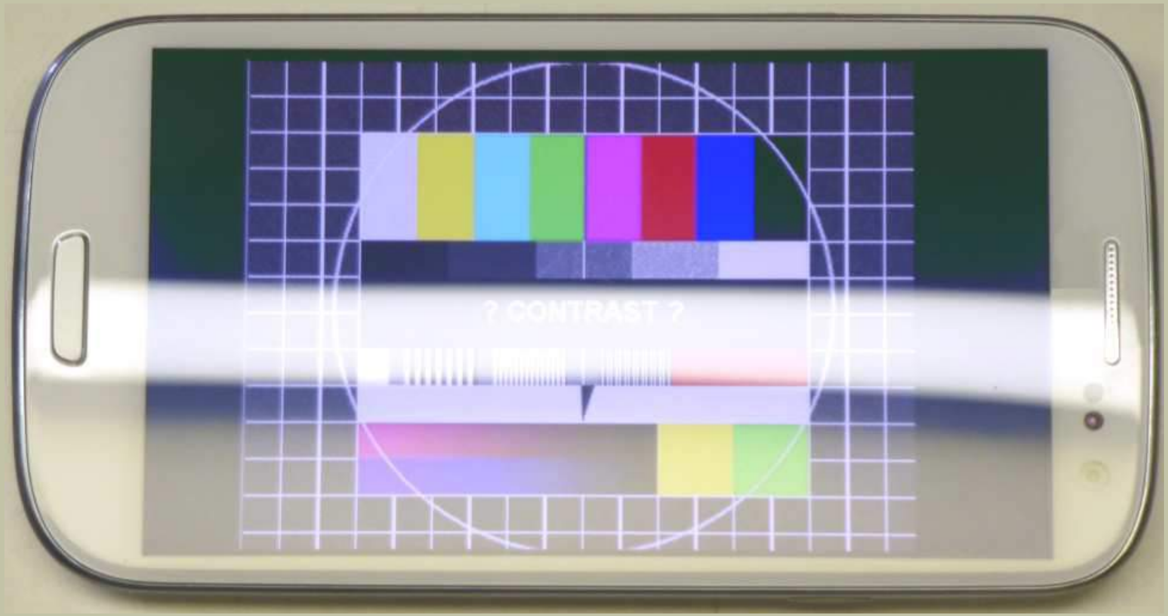
- Active member of **ISO TC159 SC4 WG2**,
- Active member of **IEC TC110**,
- Initiator of IEC TC110 HHG,
- Contributions to **ICDM-IDMS**, EC member,
- Chairman ICDM automotive displays subcommittee.

- Lectures on electronic displays at KIT,
- Seminars, professional training courses, etc.

- SID member since 1980, SID MEC chairman (past),
- SID seminars (Display measurement & modeling),
- Publications on display metrology and modeling,
- Patents in the field of display metrology,
- ...



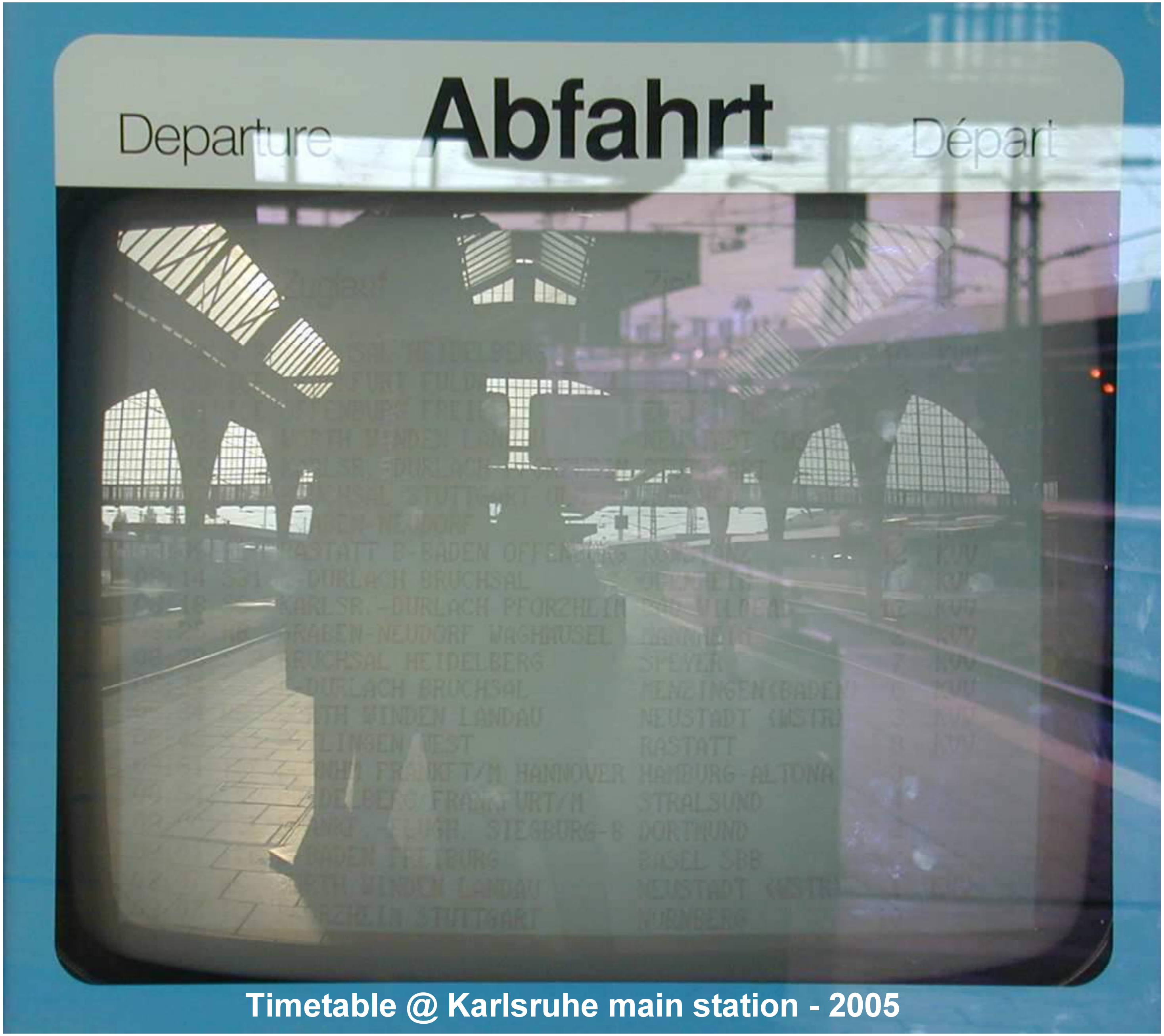
The Problem: Reflections



Reflections cause

- reduction of contrast,
- reduction of color saturation,
- glare,
- focusing conflicts.

The Problem: Reflections



Timetable @ Karlsruhe main station - 2005

Specular (mirror-like) reflections of light sources in a display screen are annoying and disturbing:

(1) they **reduce the contrast** of displayed visual information by superposition of reflected luminance, which is extremely effective in dark display regions,

(2) they **reduce the saturation of displayed colors** by superposition of white light effecting a "**bleaching of colors**", and

(3) **distinct mirror images of light sources** cause **fusion conflicts** since the human visual system instinctively tries to focus on available visual information. In this case however, the visual targets are located at different distances (display at some 40 – 80 cm and ambient light sources some meters) and they thus cannot be focused at the same time.

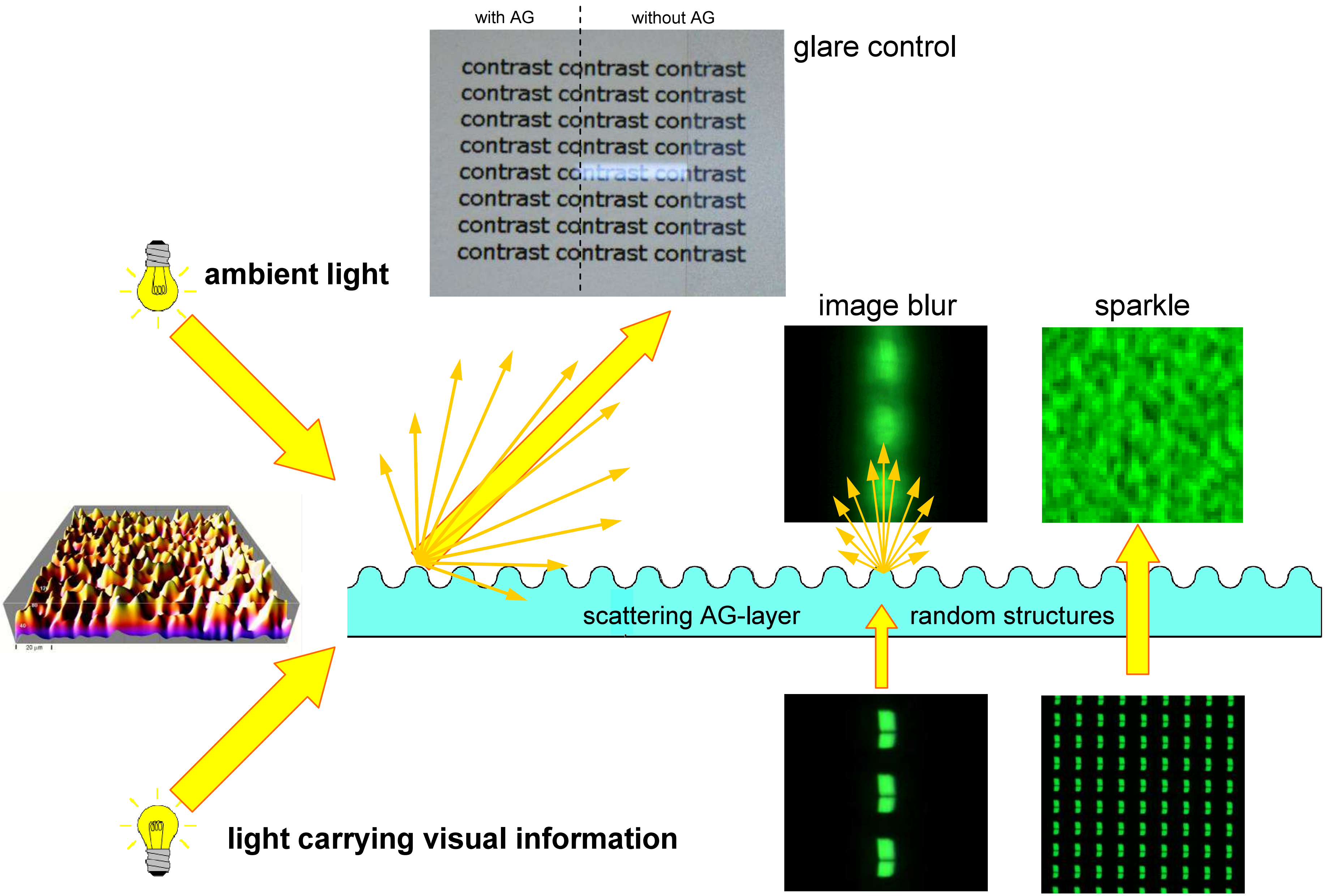
This conflict may cause headache and visual fatigue (e.g. Journal of Vision 8(3):33 (2008), 1–30).

(4) they cause **glare** that impairs the observer in various degrees (from discomfort to disability) .

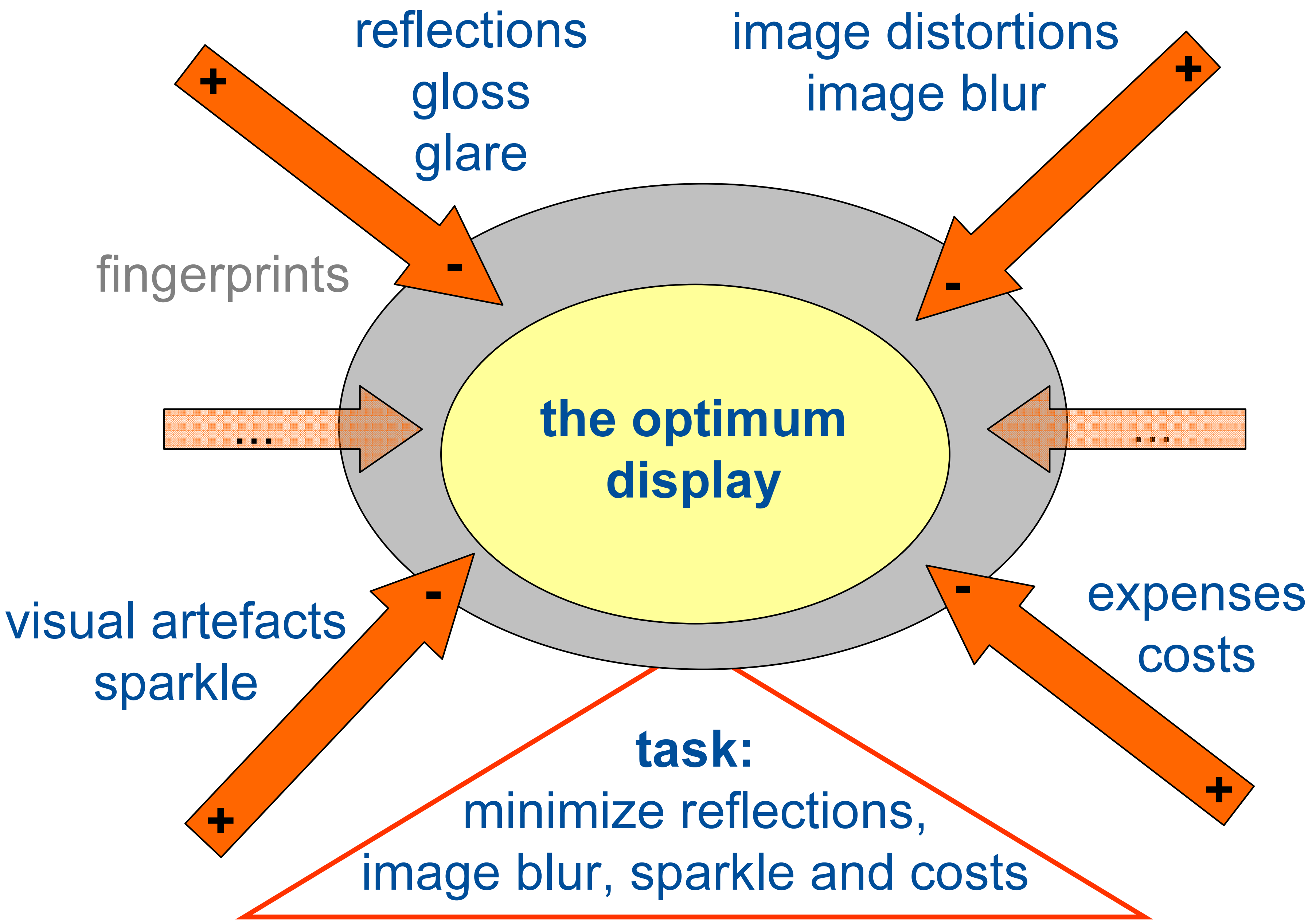
There is a cure ...

... but not without side-effects.

Optimization of Displays with an AG-Layer



Optimization Task



Content

Sparkle - an introduction

- observer and observation conditions
- electronic imaging, conditions & sampling

Spatial filtering

- convolution with a kernel with rational dimensions

Analysis in the frequency domain

- summation of harmonic amplitudes
- apparent size of sparkle granules

Filtering by imaging (undersampling)

Sparkle from intensity statistics (histograms)

Sparkle ?

Sparkle:

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

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

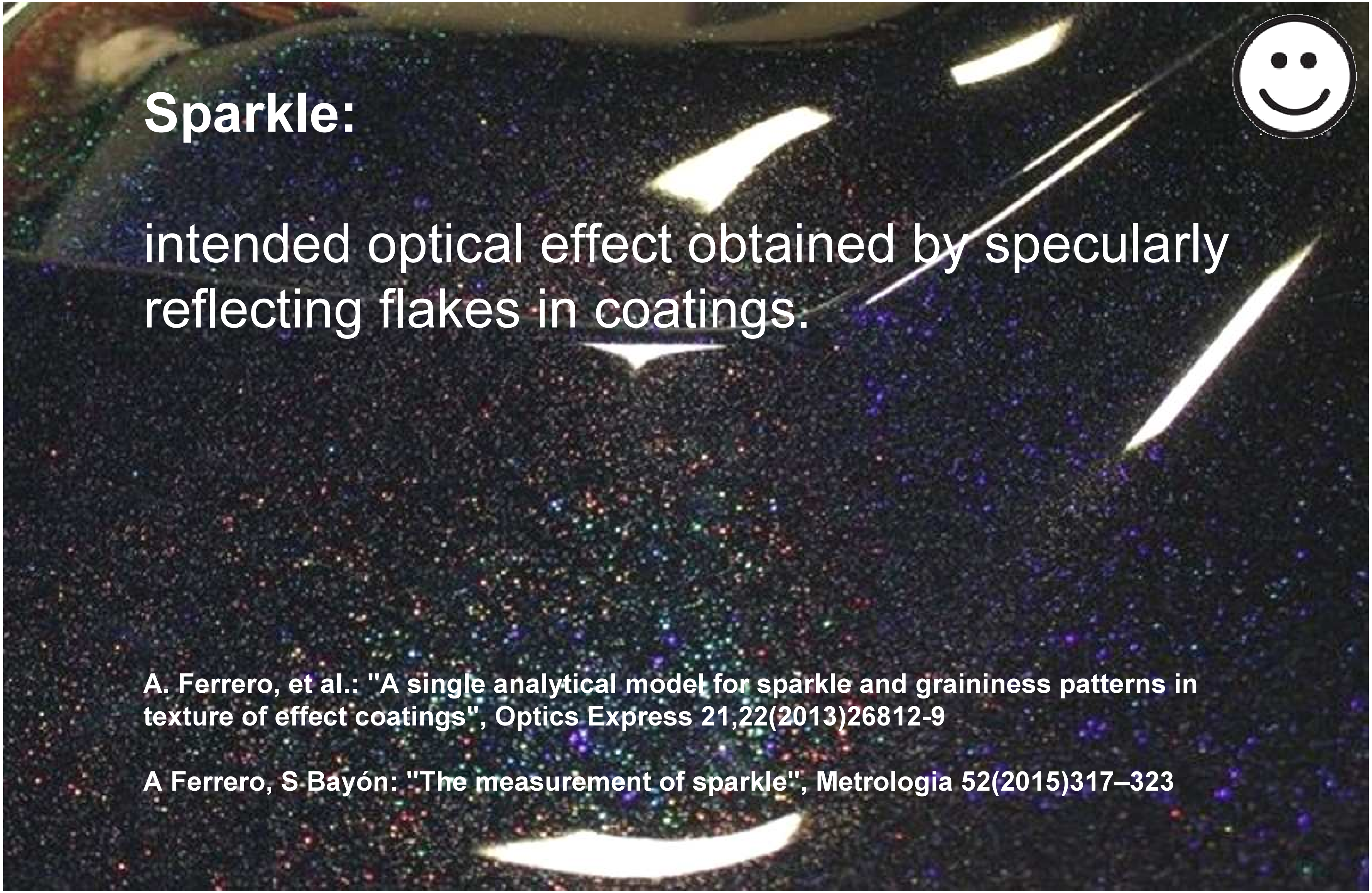
Sparkle ?

Sparkle:

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

Robert Adler in US Pat. No. 4,972,117(1990) on ***display sparkle***:

"It is well known to reduce or suppress specular reflection by roughening the front surface of the display device, which, for example, could be the glass faceplate of a CRT, or a plastic overlay. However, when such a roughened surface is used in connection with a display screen which is made up of a ***regular pattern*** of fine dots or stripes, as is generally the case with direct view color displays, a ***disturbing phenomenon known as sparkle or random moire*** arises: Interference between the spatial frequencies of the dot or stripe pattern and the similar spatial frequencies contained within the broad range of spatial frequencies that characterize a roughened surface, produces ***beats which appear to move when the observer moves***, and ***which are quite disturbing***."



Sparkle:

intended optical effect obtained by specularly reflecting flakes in coatings.

A. Ferrero, et al.: "A single analytical model for sparkle and graininess patterns in texture of effect coatings", Optics Express 21,22(2013)26812-9

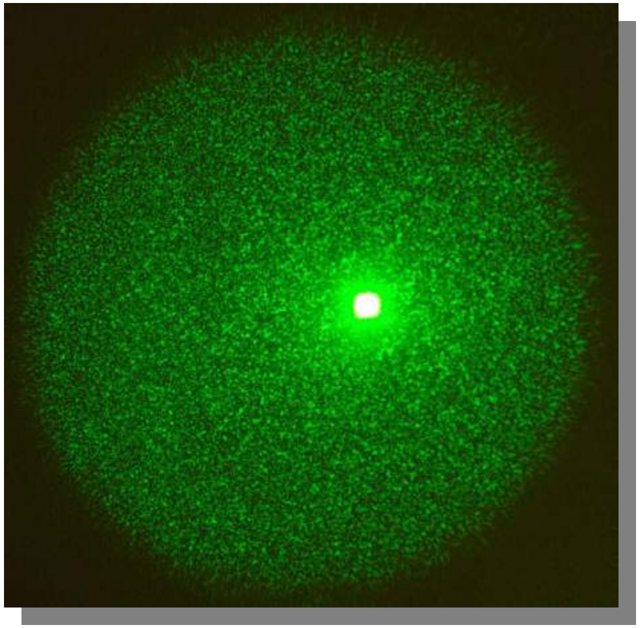
A Ferrero, S Bayón: "The measurement of sparkle", Metrologia 52(2015)317–323

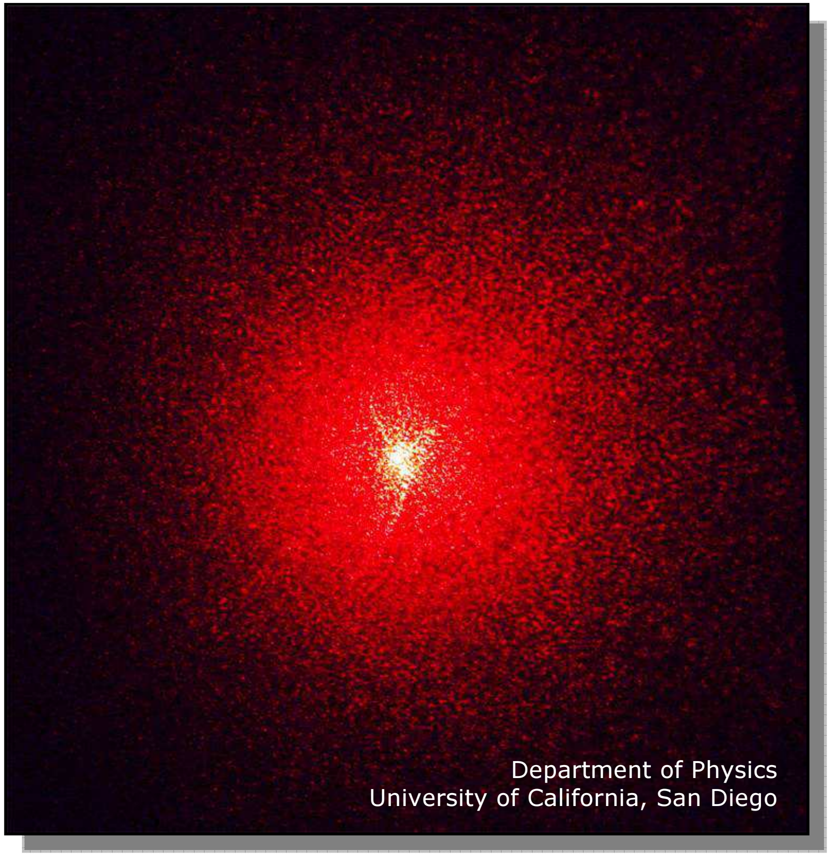
Speckle ?

A ***speckle pattern*** is an intensity pattern produced by the mutual interference of a set of wavefronts.

The speckle pattern varies randomly as a function of the observation condition.

Speckle patterns are annoying in projection display systems and need to be controlled.





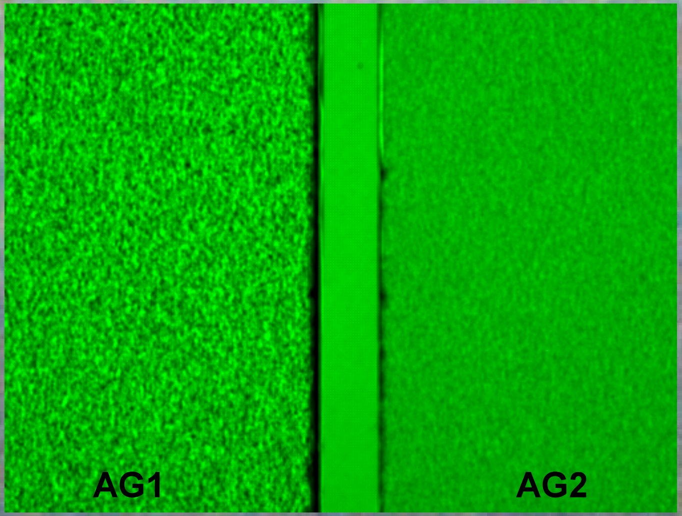
Visual Perception of Display Sparkle

We do see:

statistic intensity (and chromaticity) modulations
- vs. location on the display, and
- **vs. direction of observation.**

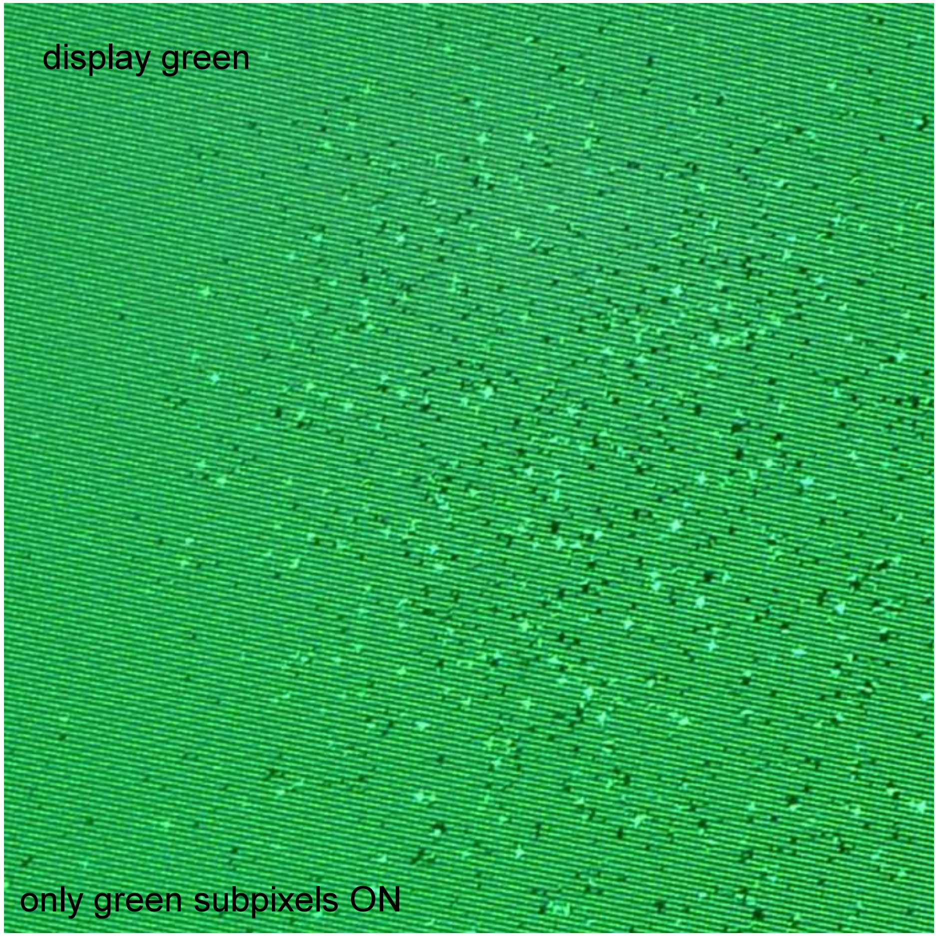
We do not see:

individual pixels of the display screen.



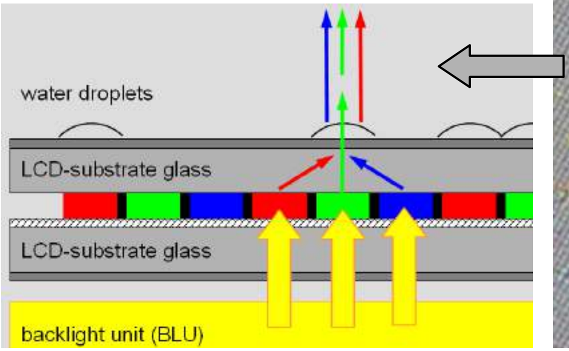
Sparkle is not restricted to one plane in space.

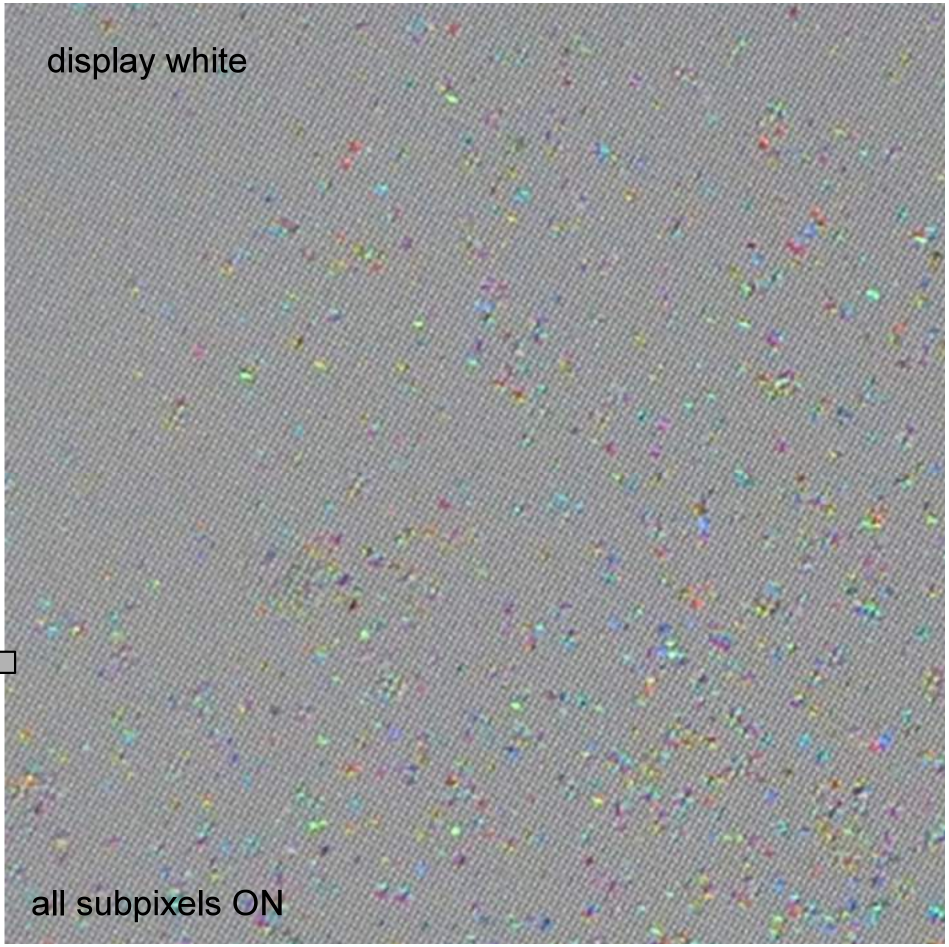
Generation of Sparkle



Water-mist sprayed onto a glossy LCD screen:
➲ droplets act as convex micro-lenses.

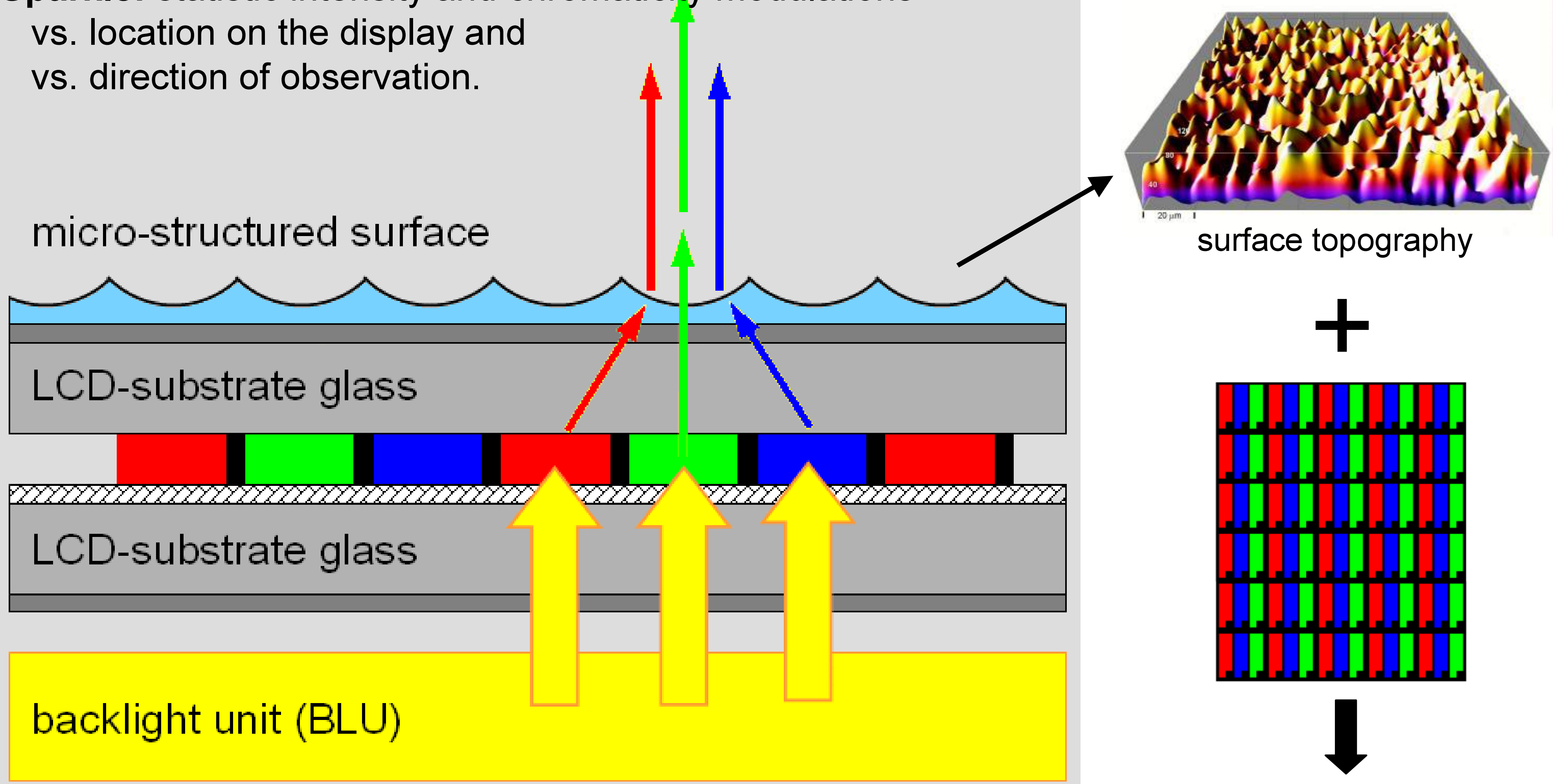
Refraction explains what we see.





Sparkle

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

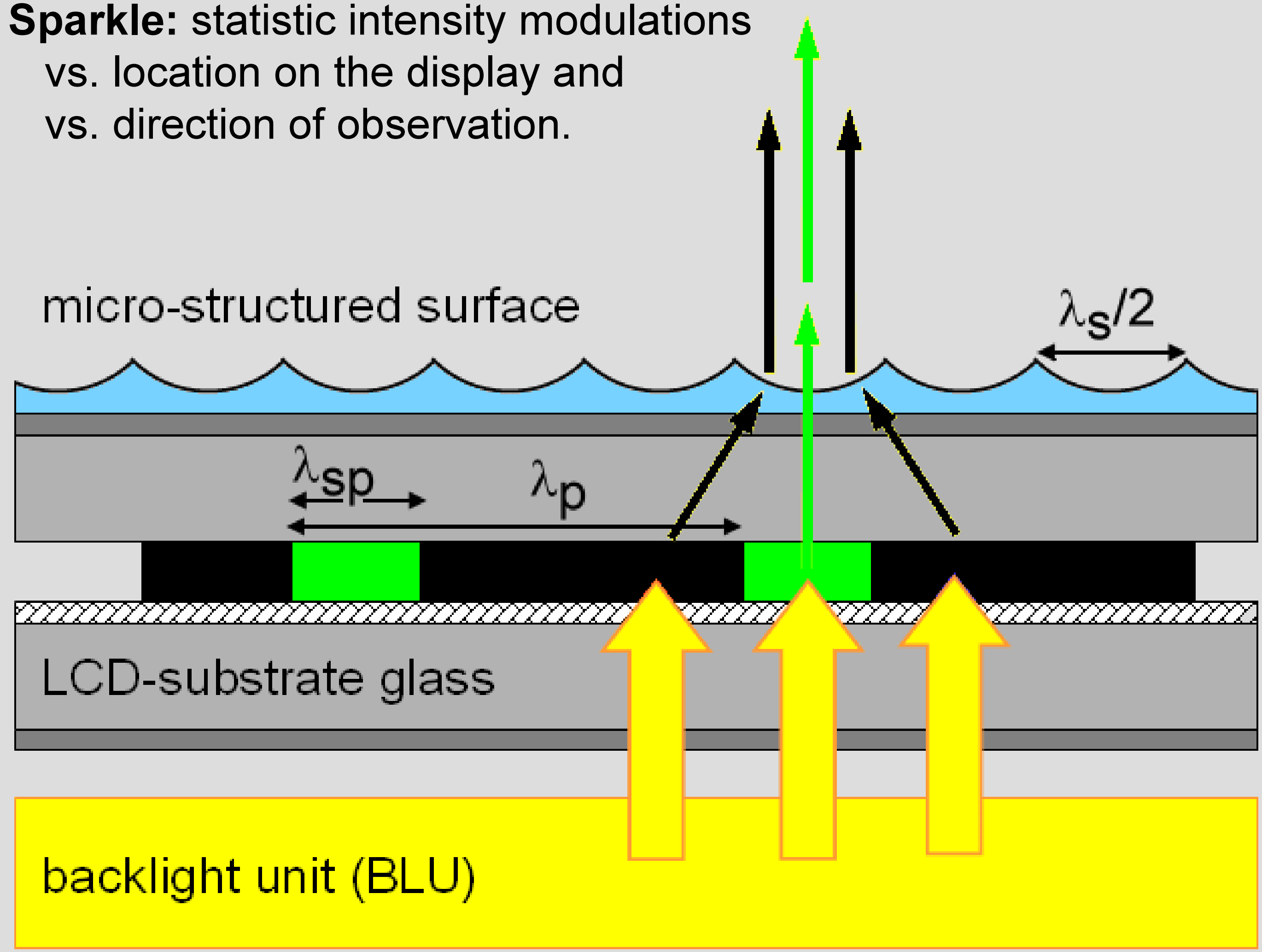


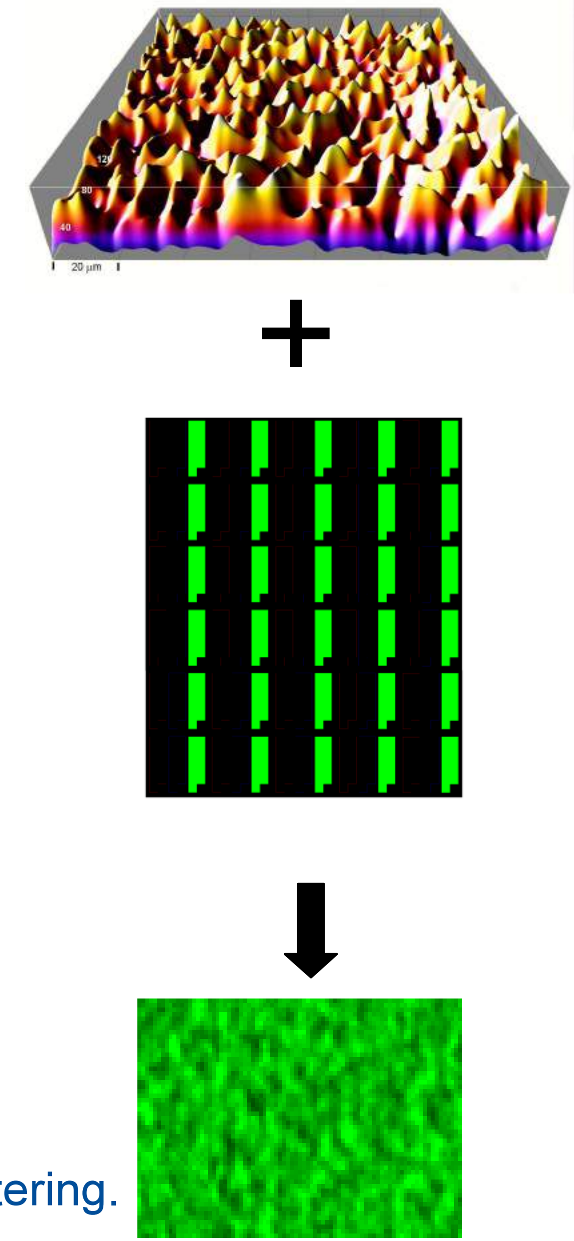
Generation of sparkle:

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

Sparkle

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

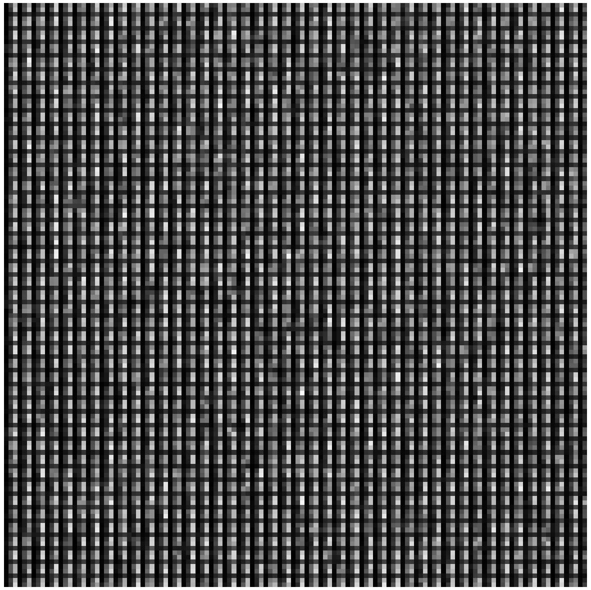




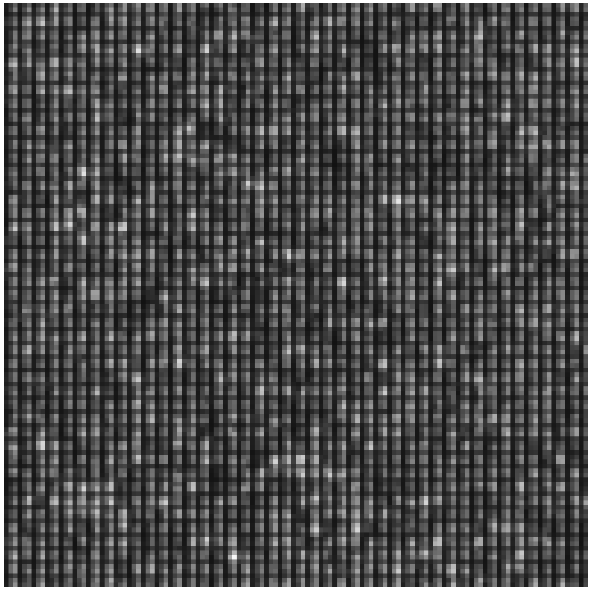
Sparkle is distinctly visible with green illumination:

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

Sparkle: Effect of Viewing-Direction

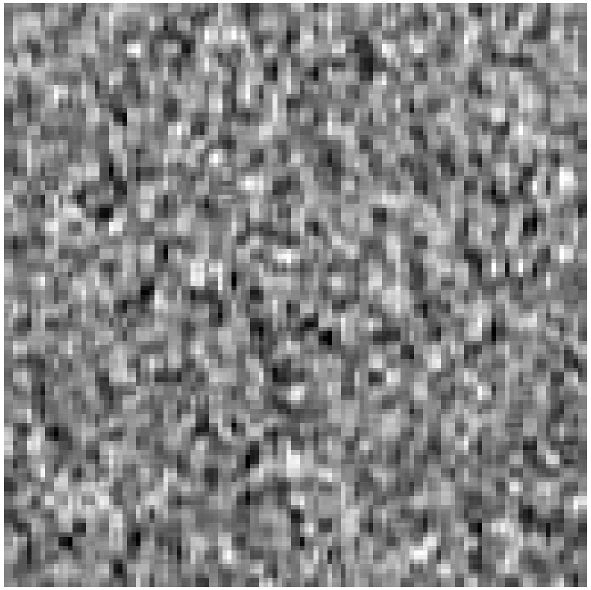


raw image



F#/2.8 $\Delta\theta = 0.25°$

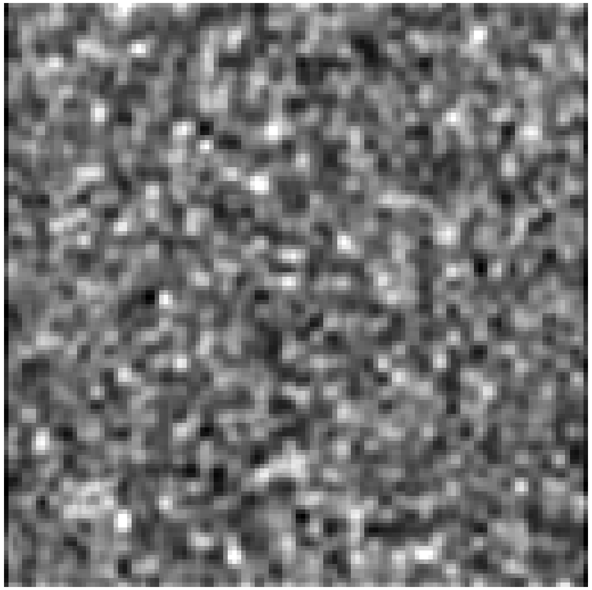
F#/8 $\Delta\theta = 0.25°$



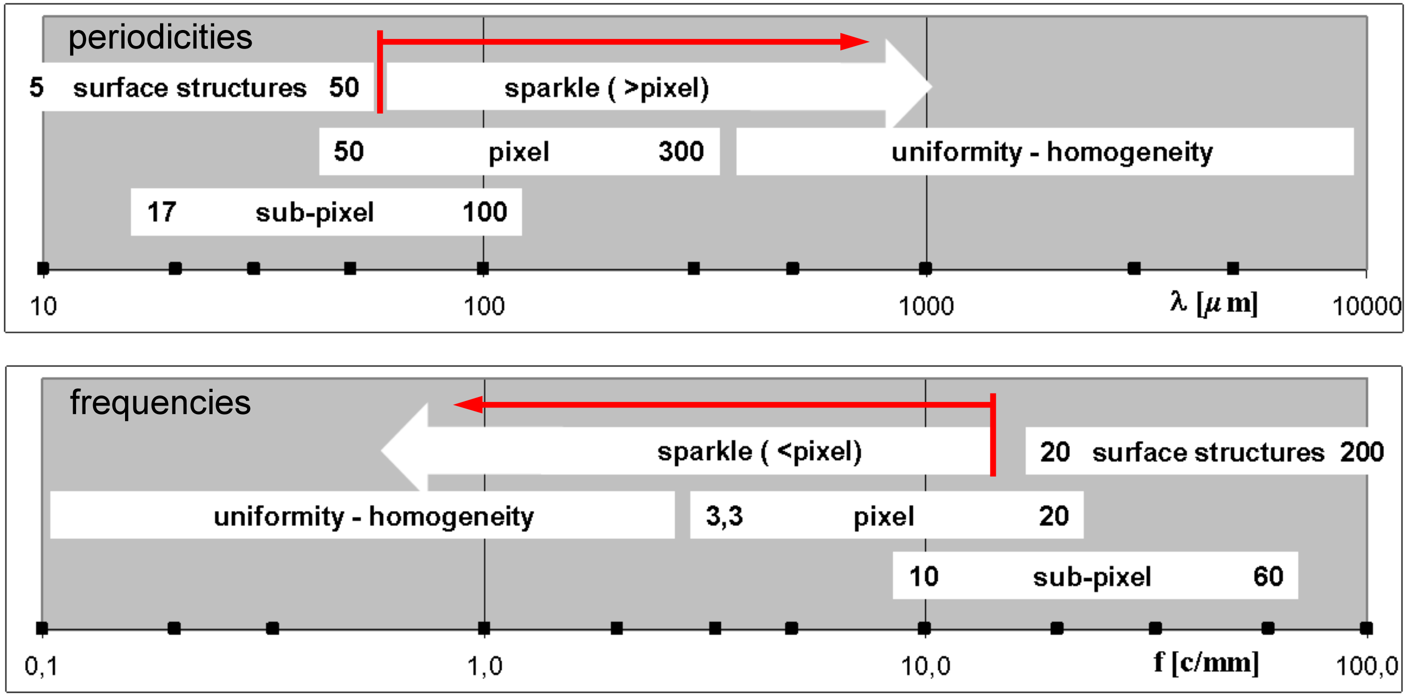
filtered image

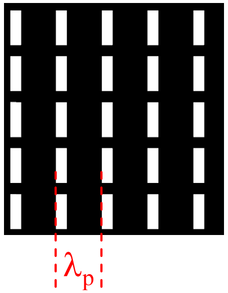
$C_{sp} = 18\%$

$C_{sp} = 8.6\%$



Dimensions and Periodicities





The 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: 0,3 mm (PC desktop monitors for office work) to about 0,05 mm (high resolution display screens for handheld devices). Subpixel dimensions thus are in the range from 0,1 mm to 0,017 mm.

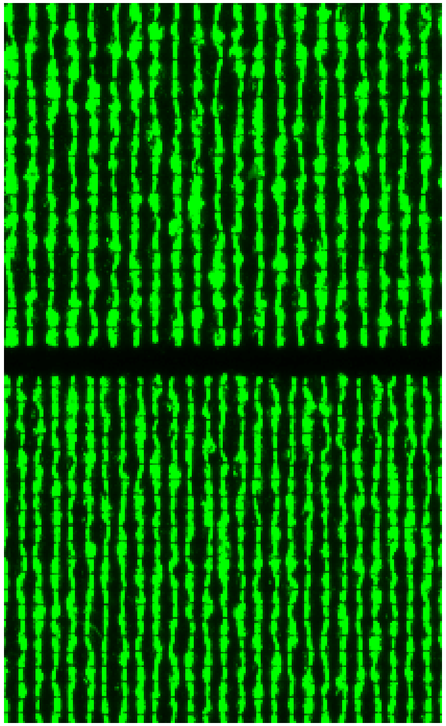
Surface structures of AG-layer with average periods in the range from 5 μm to 50 μm.

Sparkle Evaluation requires separation of

- **periodic intensity variations**

  from

- **statistic intensity modulations.**

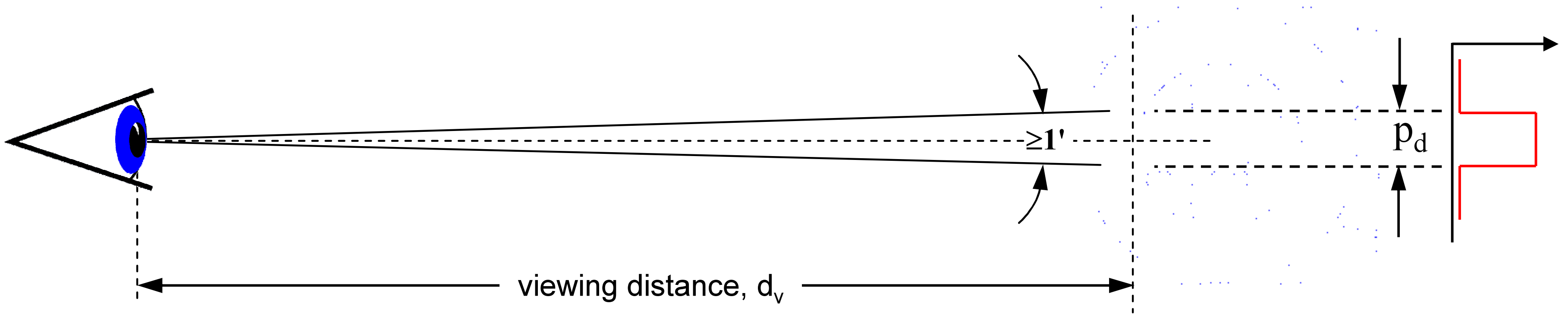


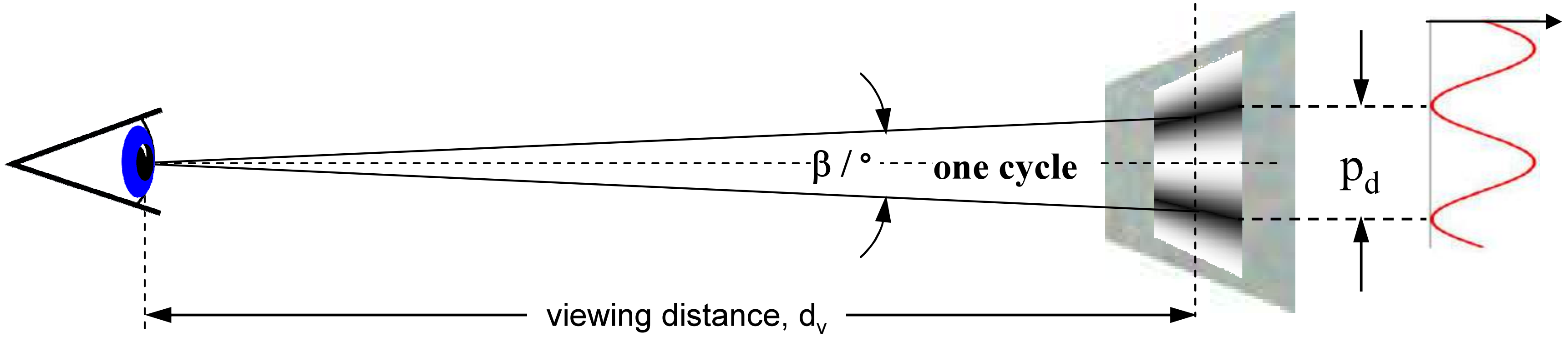
Observation of display sparkle:

The Human Observer: Visual Acuity

Visual acuity: the ability of the ***human eye*** to distinguish small features
@ good contrast, photopic adaptation, etc.

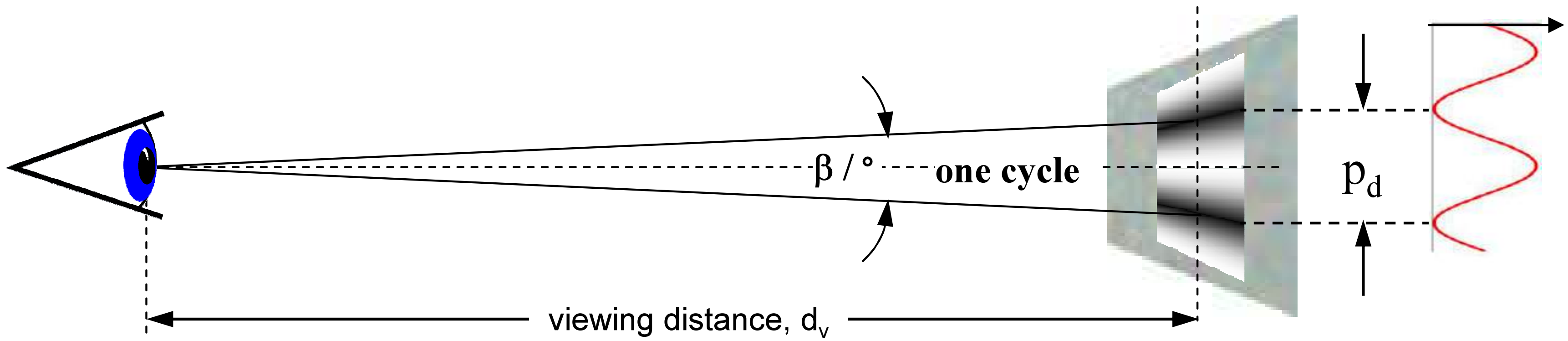
Visus = 1: A feature subtending 1' (1°/60) can just be distinguished.





Spatial frequency of a *periodic visual target* = #cycles / degree visual angle.

Visual Perception of Sparkle

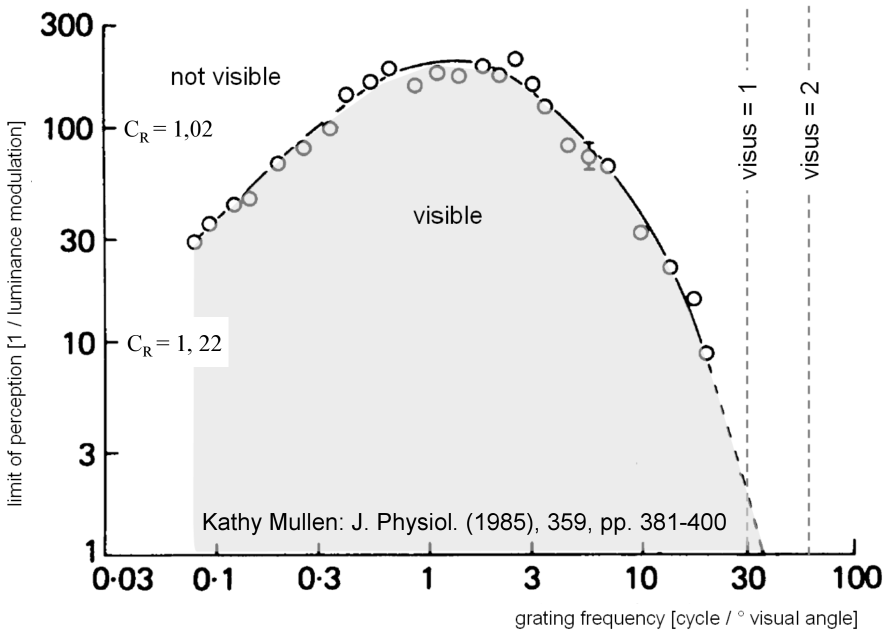


Observation condition for display sparkle:

Adjustment of viewing distance

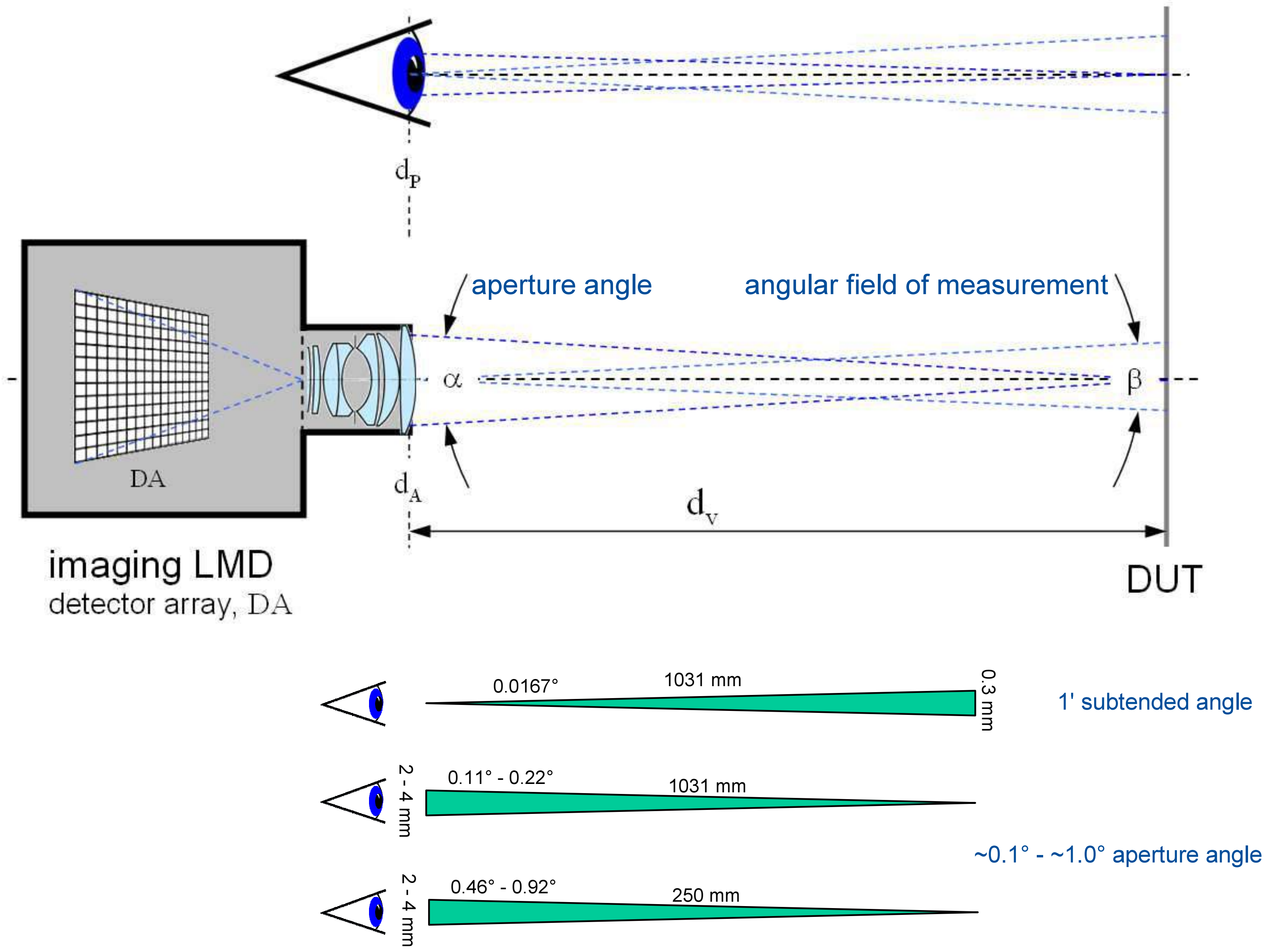
to make pixel pattern disappear while sparkle remains visible.

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



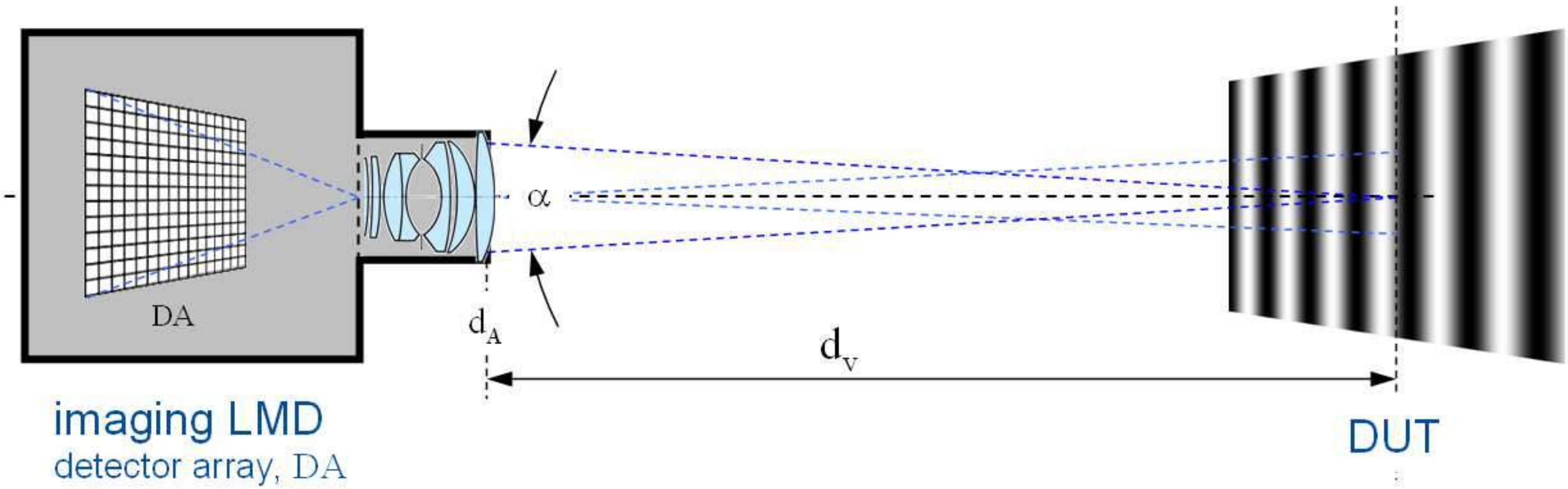
contrast sensitivity function @ green light

Observation and Imaging



The Nyquist–Shannon sampling theorem

establishes a **sufficient condition** for a sampling rate that permits a discrete sequence of samples to capture all the information from a continuous-time signal of finite bandwidth.

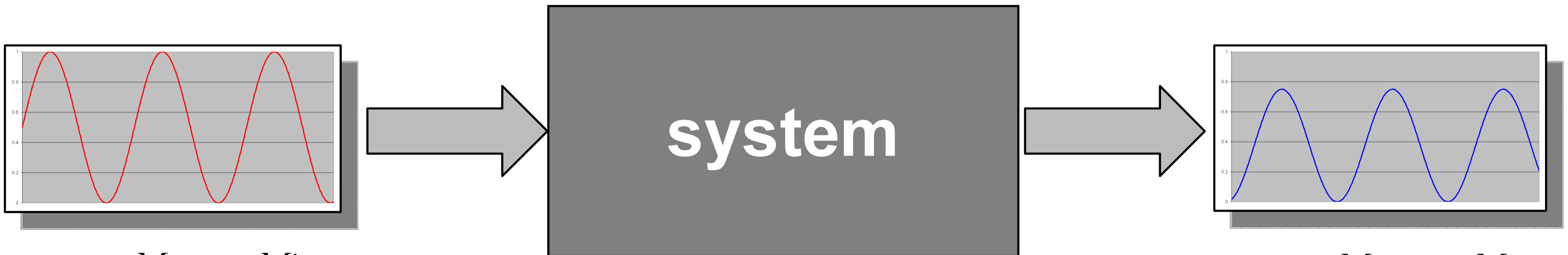


If a continuous light intensity distribution, $L(x, y)$, of the DUT contains no spatial frequencies higher than *B* (cycles / distance x, y), the distribution is completely specified by sampling it with a series of pulses placed 1/(2·*B*) apart in both x and y direction.

➲ For each display pixel we need >2 LMD pixels in x and in y direction.

Electronic Imaging: Detector Array and Optics

The MTF specifies the attenuation of sine-patterns (signals) of varying frequency by a system.

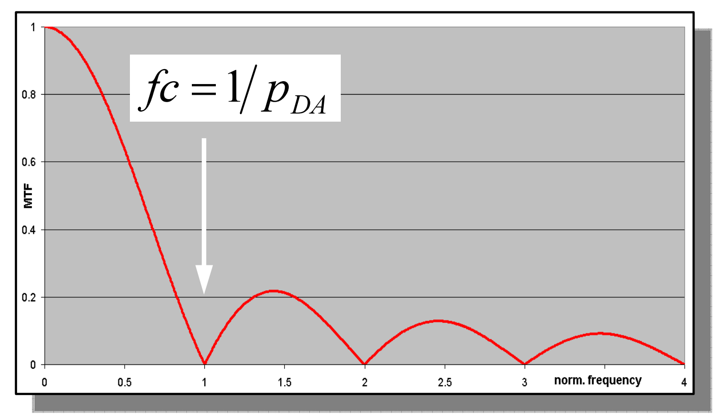


$$M_{in} = \frac{Max_{in} - Min_{in}}{Max_{in} + Min_{in}} \qquad MTF = \frac{M_{out}}{M_{in}} \qquad M_{out} = \frac{Max_{out} - Min_{out}}{Max_{out} + Min_{out}}$$

In an electronic imaging system the MTF of the system is given by the MTF of the optics and the MTF of the detector array.

The elements of the detector array integrate incoming flux over their light-sensitive area.

$$MTF_{\text{detector}} = \left| \frac{\sin(\pi \cdot p_{DA} \cdot f)}{\pi \cdot p_{DA} \cdot f} \right|$$



The cutoff frequency of the MTF of the detector array (first zero), f_c, is given by the pitch of its elements, p_{DA}.

MTF - Human Eye - Optics

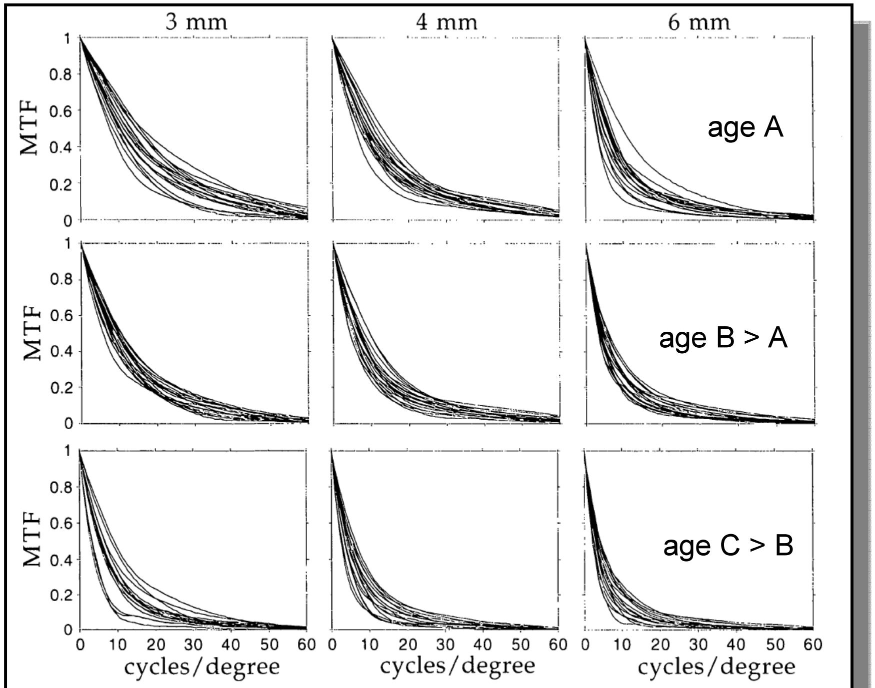
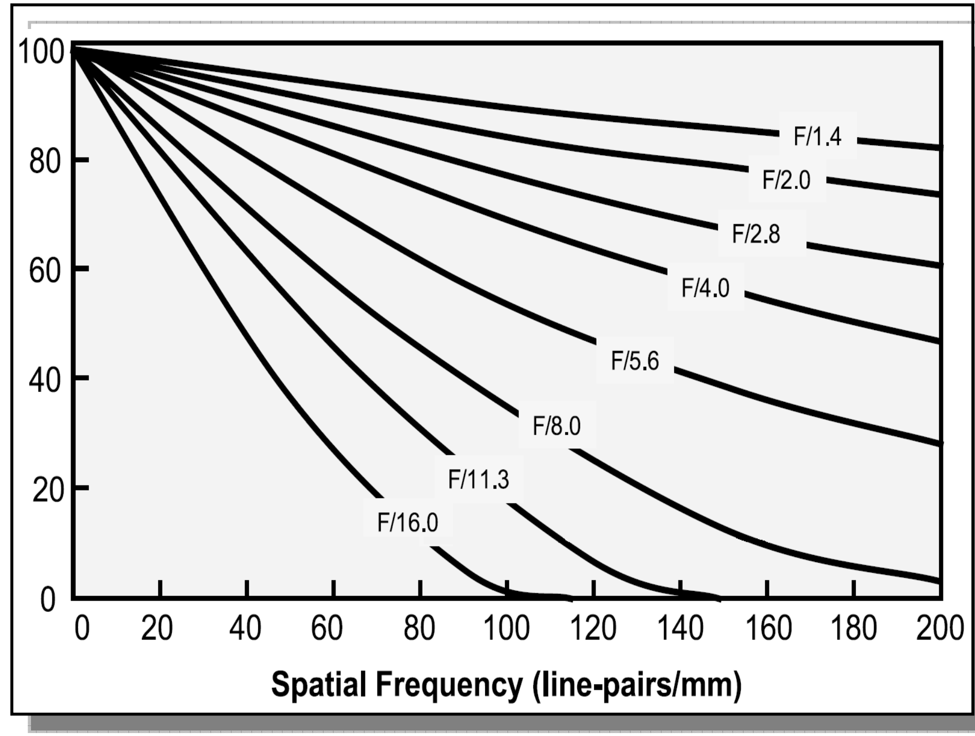


FIGURE 5. Modulation transfer functions (MTFs) for every subject tested in the three age groups (A, B, C) with three pupil diameters: 3 mm, 4 mm, and 6 mm.

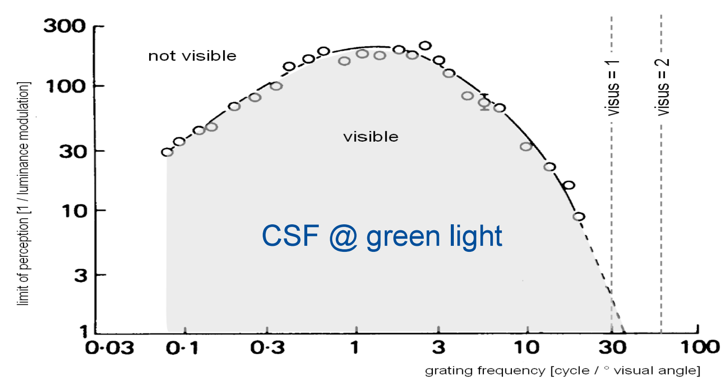


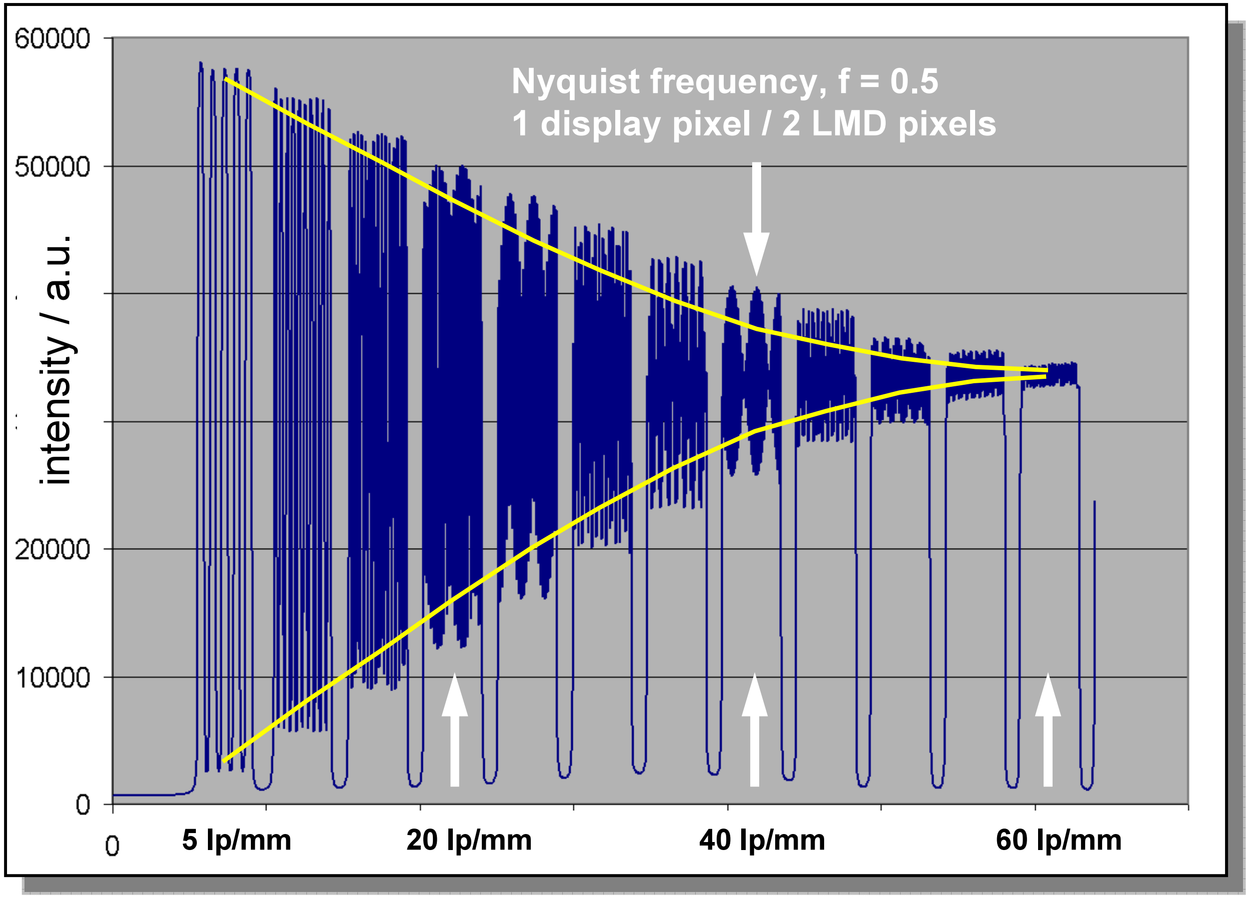
Antonio Guirao, et al.: "Average Optical Performance of the Human Eye as a Function of Age in a Normal Population", Investigative Ophthalmology & Visual Science, 1999, 40, 1, pp. 203-213

Image Sensors and Signal Processing for Digital Still Cameras, J. Nakamura, Editor, 2006

The MTF of the human eye specifies the physical imaging process, it is not "what we see".

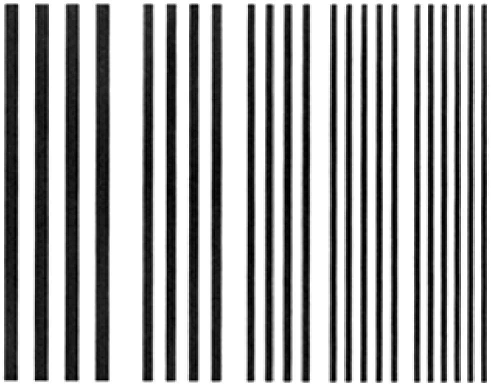
The ***visual experience*** is specified by the CSF, the ***contrast sensitivity function***.



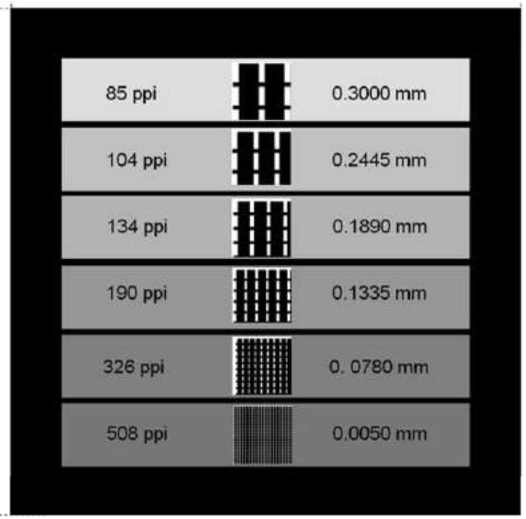


A good **estimation of the MTF (CTF)** of the imaging system is obtained with two targets.

Sampling ranges from 1 μm / LMD-pixel to 1mm / pixel.
with different lenses and distances.

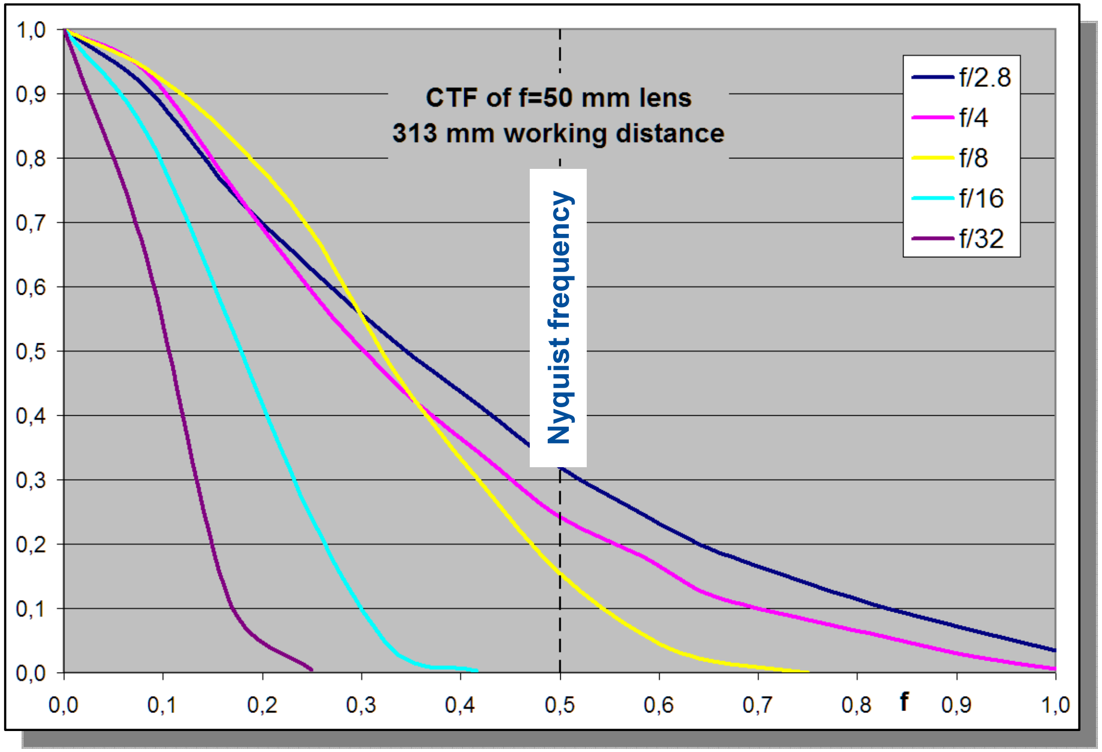


variable frequency test target, with BLU



proprietary pixel pattern array, with BLU

Effect of Lens Aperture on MTF of Imaging System



norm. frequency

Effect of lens aperture on the MTF / CTF
of an electronic imaging system with:
f = 50 mm, at a working distance of 313 mm.

The ***sampling rate*** (pixel ratio), in the context of this work, is specified as

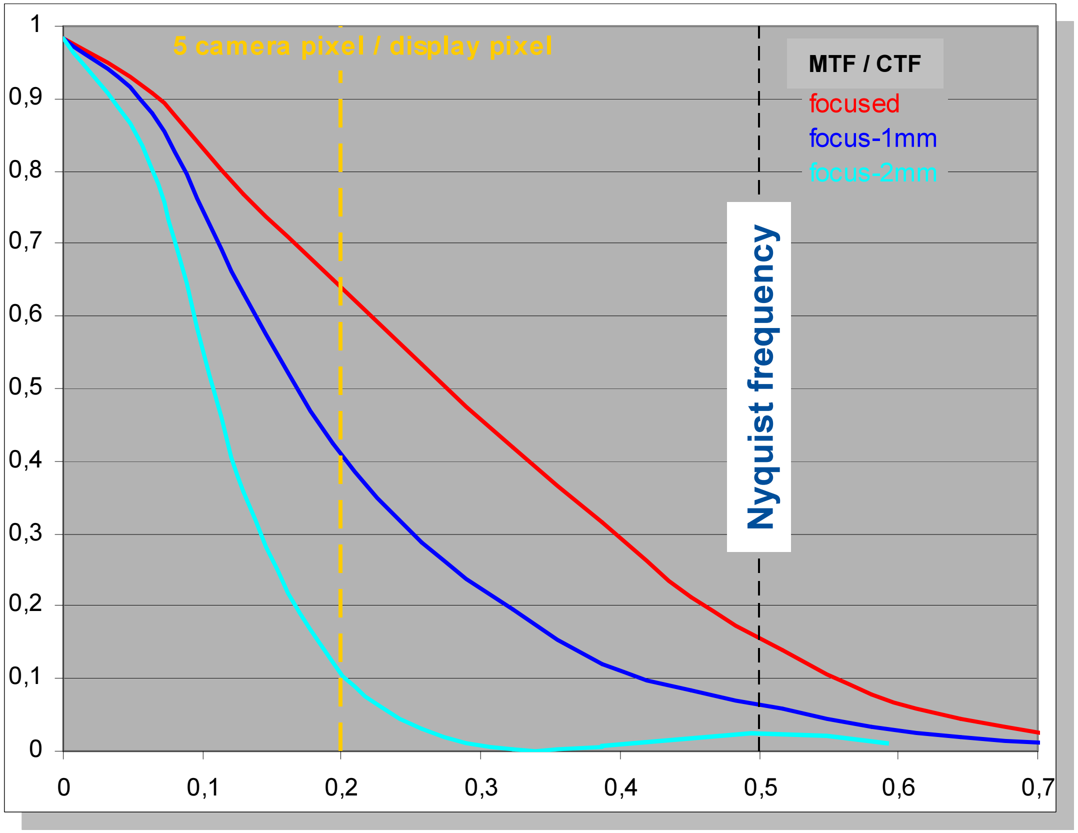
r_s = *LMD pixels / display pixel*.

The ***spatial frequency*** is the reciprocal of the sampling rate, given in terms of

f = 1/r_s = *disp. pix. / LMD pixel*

The lens aperture should be adjusted to suppress components above the Nyquist frequency
to avoid aliasing.

Effect of Defocus on MTF of Imaging System



Effect of de-focus on the MTF / CTF of an electronic imaging system
with f = 50 mm, F#5.6,
at a working distance of 200 mm.

The ***sampling rate*** (pixel ratio), in the context of this work, is specified as

$$r_s = LMD\ pixels\ /\ display\ pixel.$$

The ***spatial frequency*** is the reciprocal of the sampling rate, given in terms of

$$f = 1/r_s = disp.\ pix.\ /\ LMD\ pixel$$

The lens focus should be carefully adjusted to avoid uncontrolled LP-filtering.

Sampling of Displays

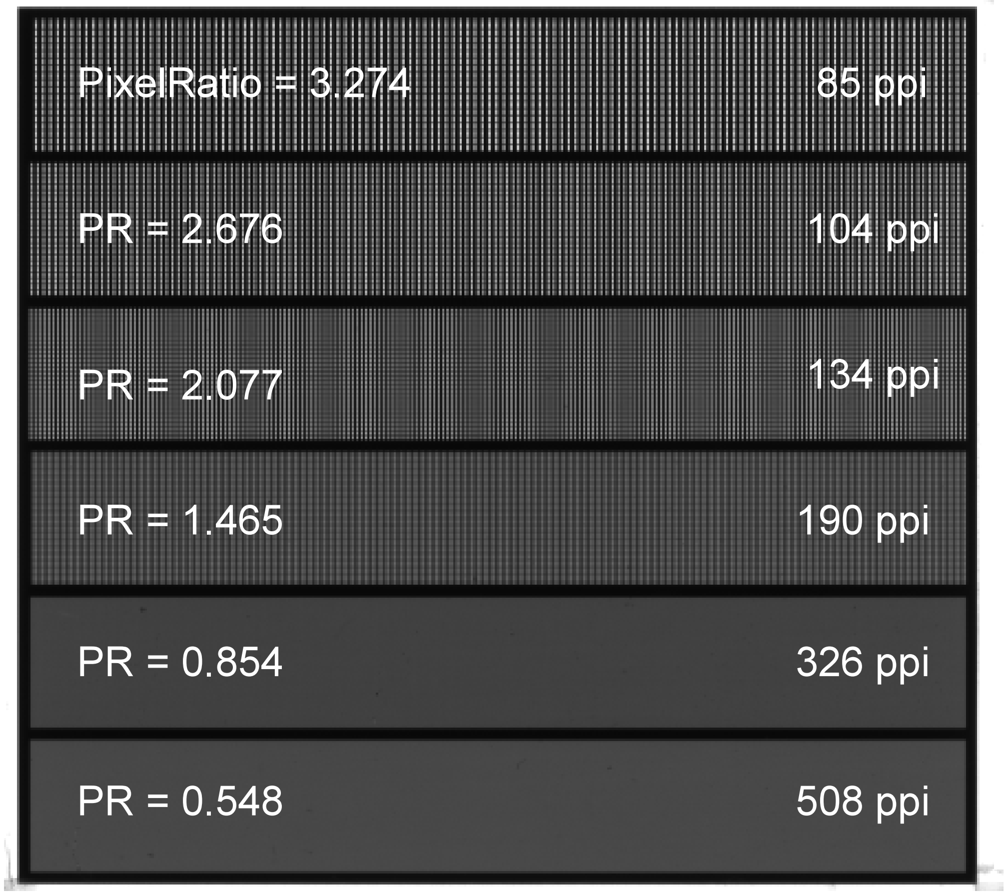
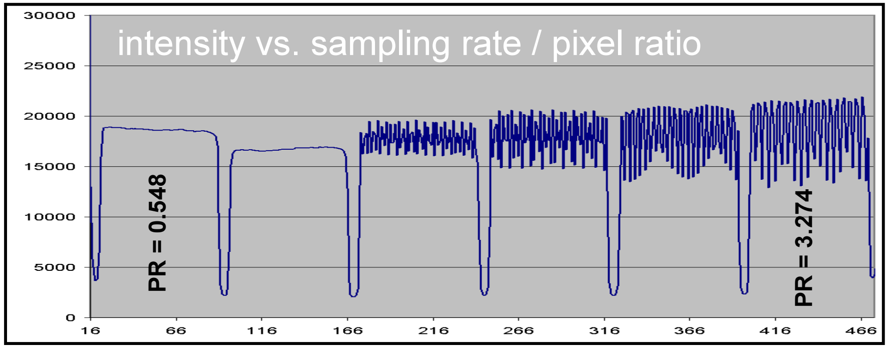
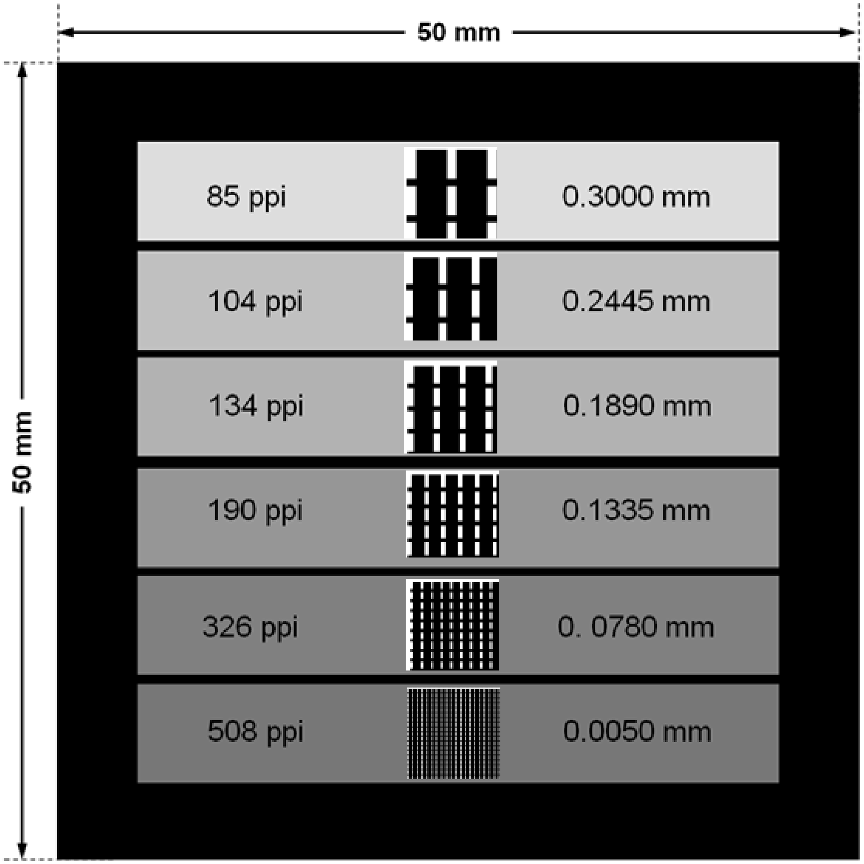
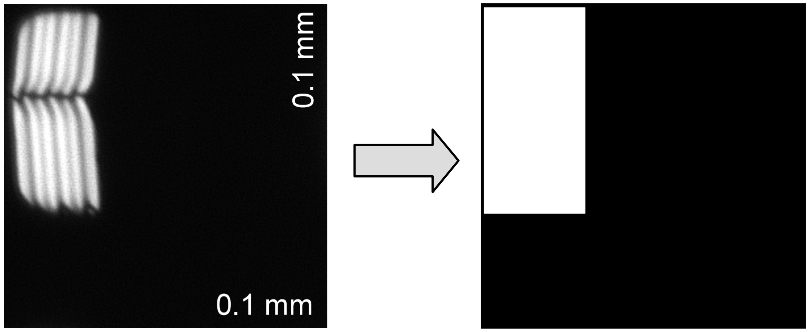


Image of the bare pixel pattern matrix



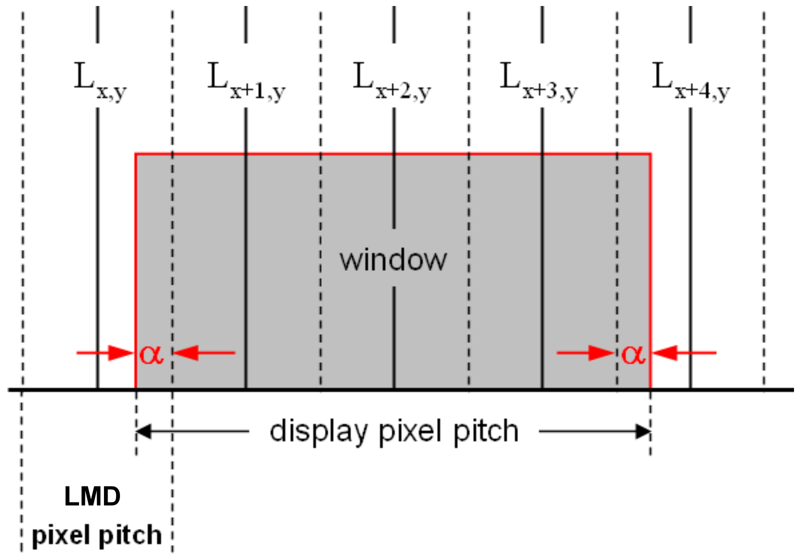




Real pixel - G sub-pixel
FFS-LCD @ 254 ppi

idealized pixel
85 ppi - 508 ppi

1D case

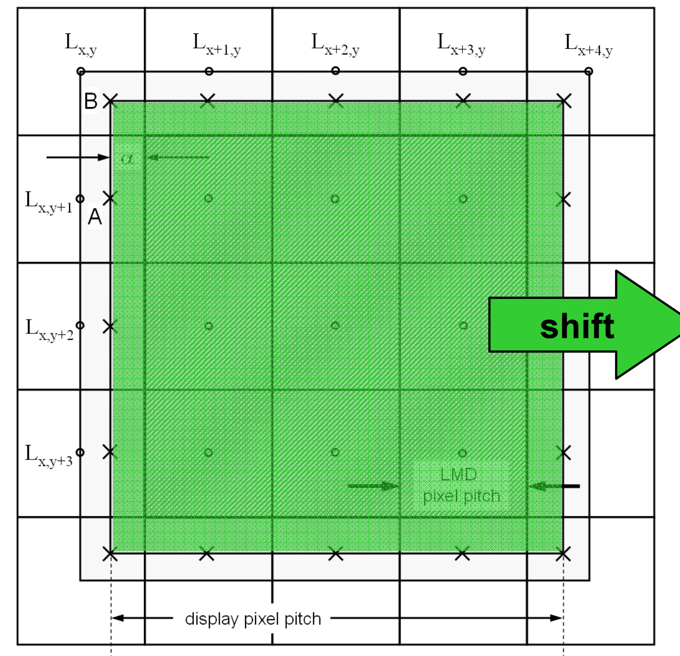


H → V

V → H

separability

2D case



$$\mu_i = \left[\alpha \cdot L_{i,y} + \sum_{j=1}^{P} L_{i+j,y} + \alpha \cdot L_{i+P+1,y}\right] / (P - 1 + 2\alpha)$$

$$L^*(x,y) = L * K = \sum_{s=-a}^{a} \sum_{t=-a}^{a} K(s,t) \cdot L(x+s, y+t)$$

with a = (k – 1)/2

1D ***moving window averging filter***
with arbitrary window dimensions.

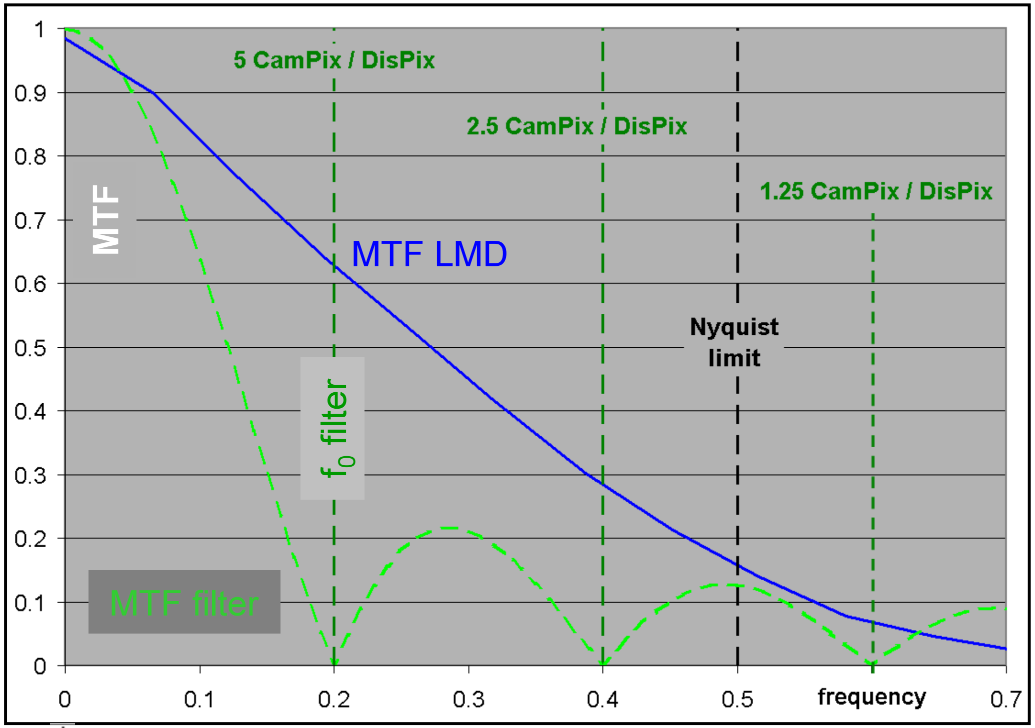
Easily implemented in spread-sheet software.

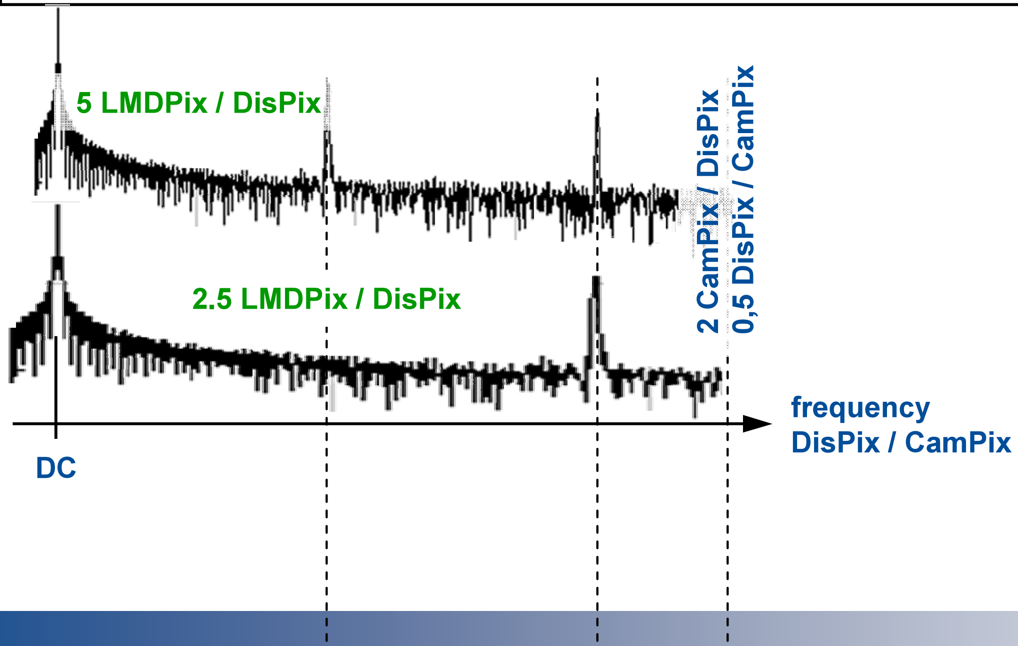
$$\begin{array}{c} \begin{bmatrix} \alpha^2 & \alpha & \alpha & \alpha & \alpha^2 \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha^2 & \alpha & \alpha & \alpha & \alpha^2 \end{bmatrix} \cdot \dfrac{1}{S_W} \\ \begin{array}{ccccc} -a & \dots & \dots & \dots & +a \end{array} \end{array}$$

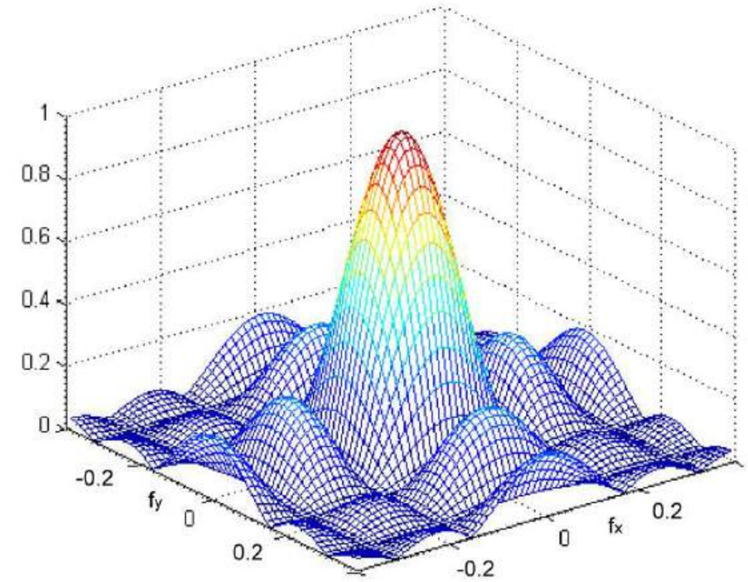
5x5 filter kernel (K = 5), ***K(s,t)***, for sampling rates r_S > 3 [LMD pixels per display pixel].

$$S_W = (K-2)^2 + 4(K-2)\alpha + 4\alpha^2$$

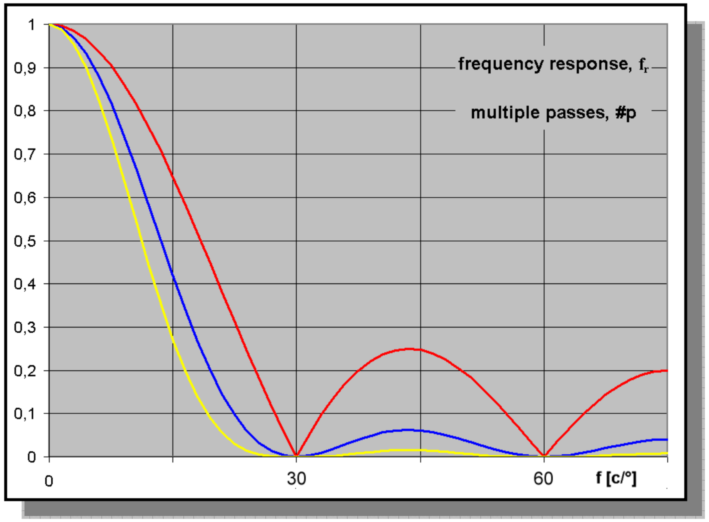
Spatial Filtering in the Frequency Domain





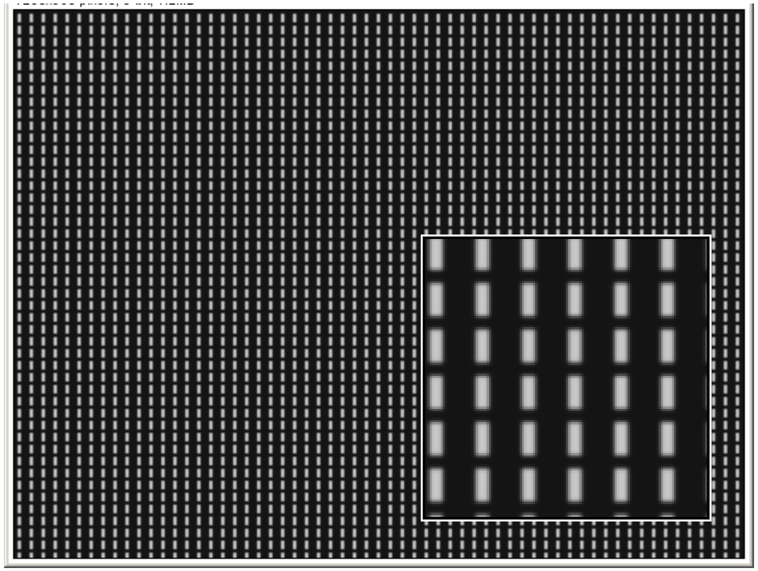


Frequency response of spatial filter



Frequency response of multiple filter passes

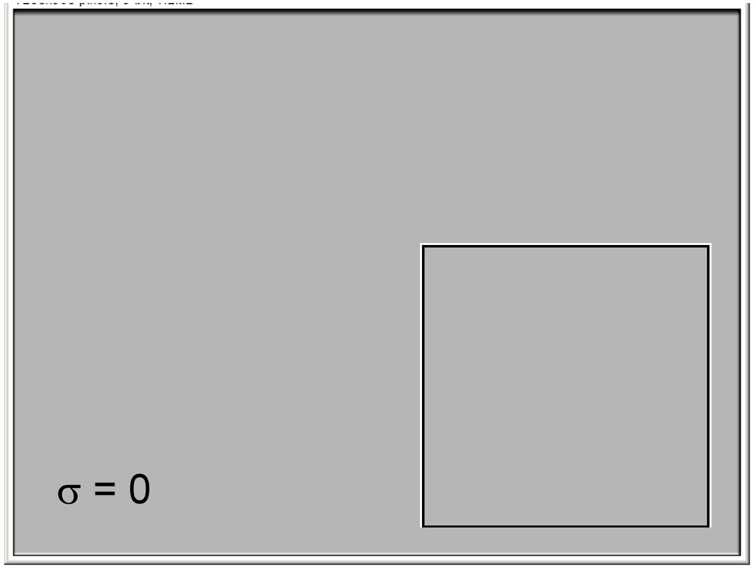
Spatial filtering (convolution) with rational kernel

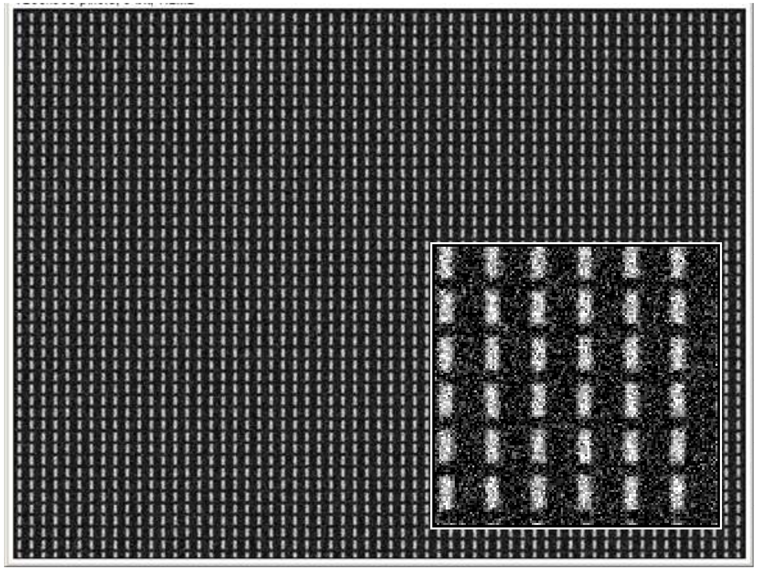


bare pixel matrix without noise

filtering

Sparkle level = σ / μ

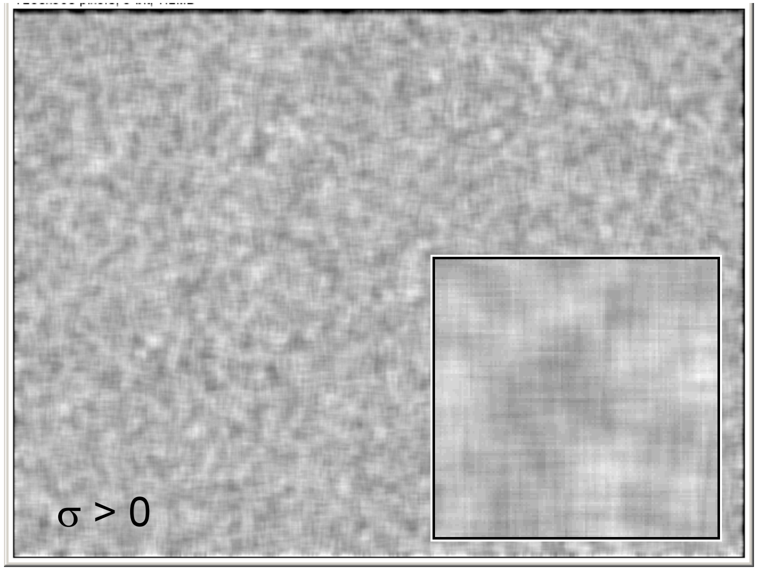




pixel matrix with noise

filtering

Sparkle level = σ / μ



Sparkle Evaluation

Single Image Method (SIM)

Record image of pixel matrix with AG-layer,

➲ **evaluate pixel ratio**

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

Sparkle level (SIM) = σ / μ

Difference Image Method (DIM)

Record first image of pixel matrix with AG-layer,

➲ **evaluate pixel ratio**

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 (DIM) = σ / μ

μ from original images

Evaluate

Evaluate

Sparkle level (SIM) < Sparkle level (DIM)

Sparkle Evaluation

Single Image Method (SIM)

Record image of
pixel matrix with AG-layer,

➲ **evaluate pixel ratio**

Evaluate

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

Sparkle level (SIM) = σ / μ

Difference Image Method (DIM)

Record first image of
pixel matrix with AG-layer,

➲ **evaluate pixel ratio**

Shift AG-layer (some mm).

Record second image
of pixel matrix with AG-layer.

Evaluate

Calculate *difference image*

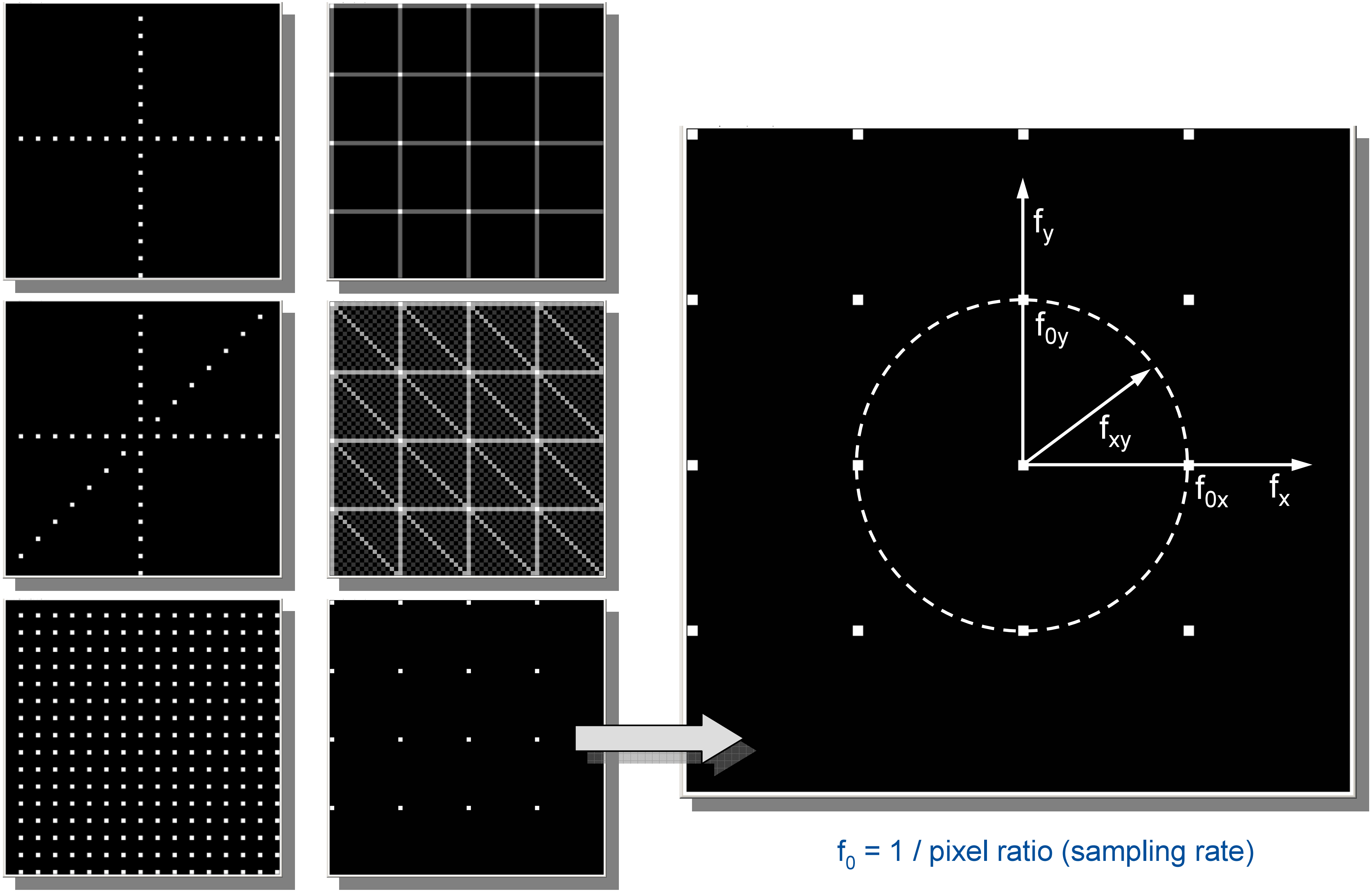
Apply spatial filtering to remove periodic modulations caused by the pixel matrix of the display.

Sparkle level (DIM) = σ / μ

μ from original images

Sparkle level (SIM) = Sparkle level (DIM) / $\sqrt{2}$

2D Discrete Fourier Transformation



f_0 = 1 / pixel ratio (sampling rate)

space

frequency - log intensity

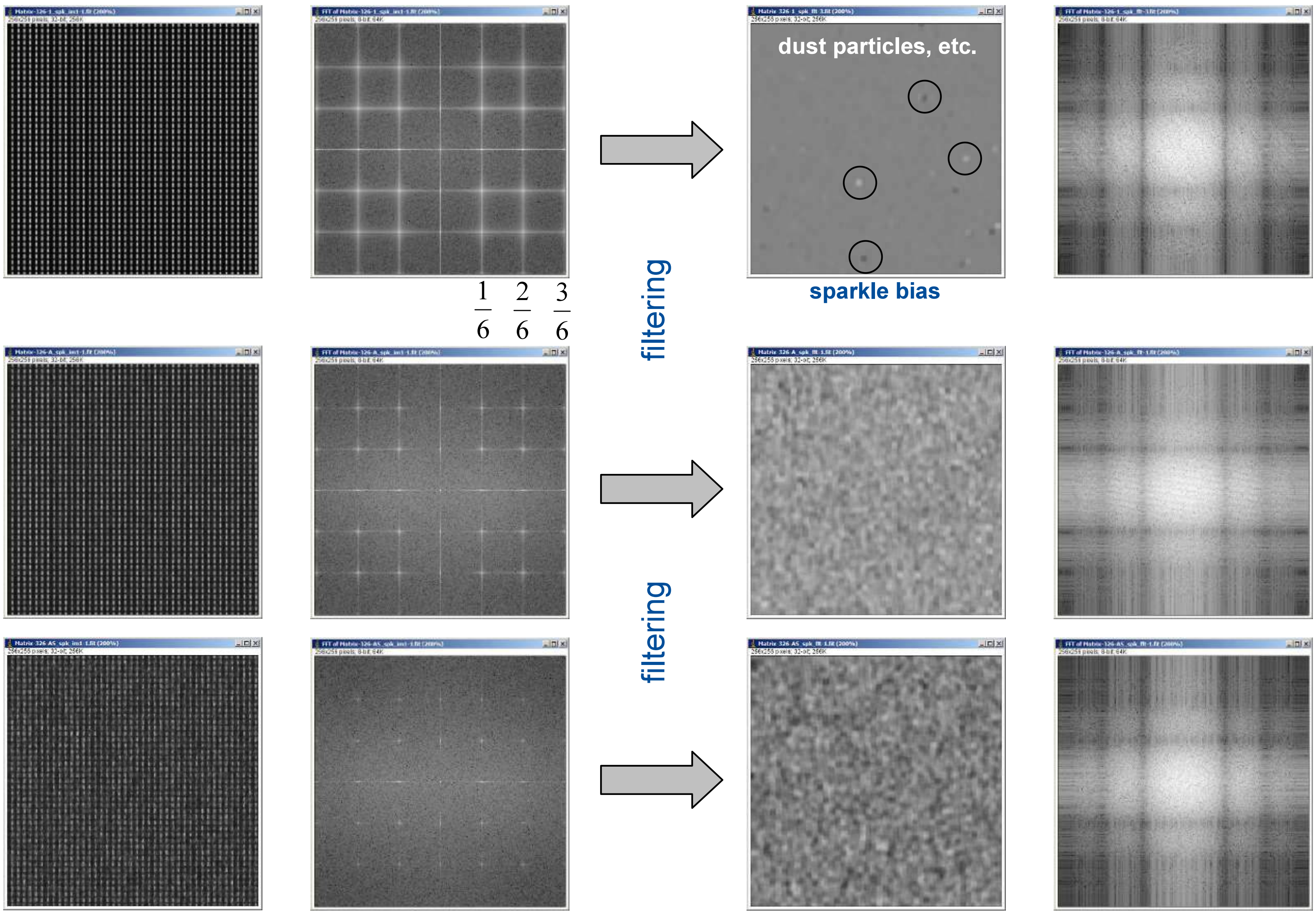
Sparkle in the Frequency Domain

bare pixel matrix

pixel ratio = 6

+ AG 1

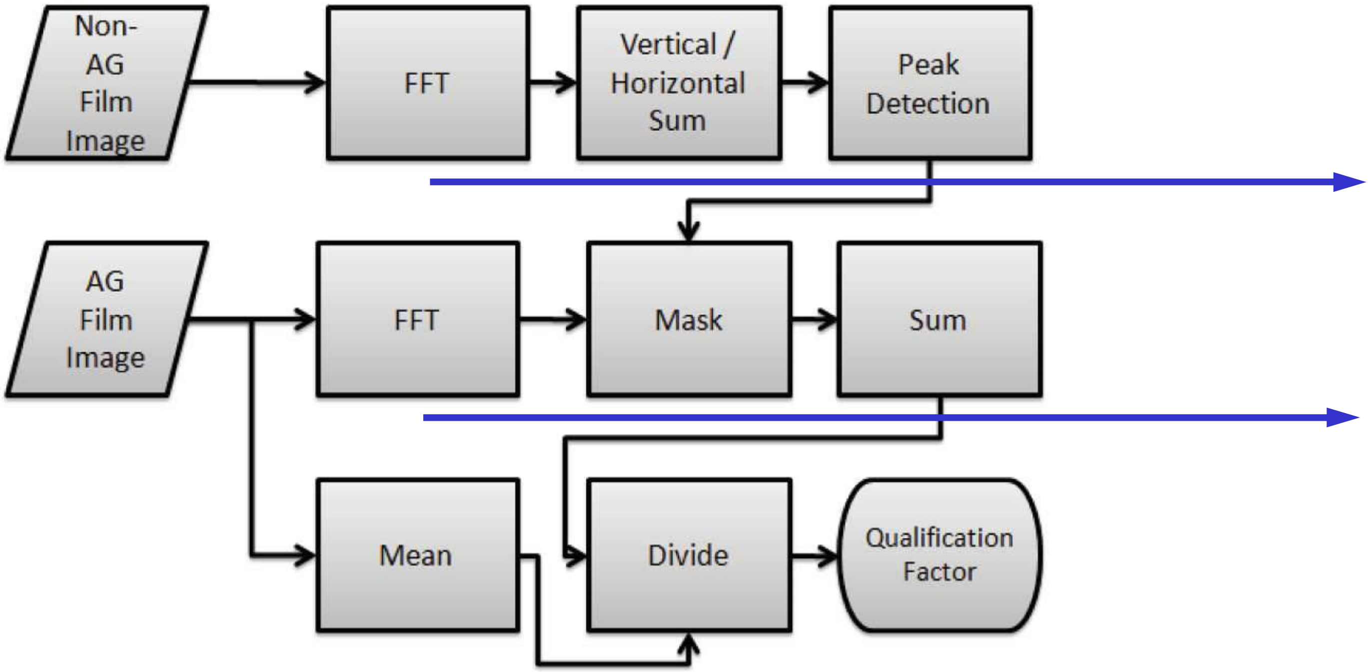
+ AG 2

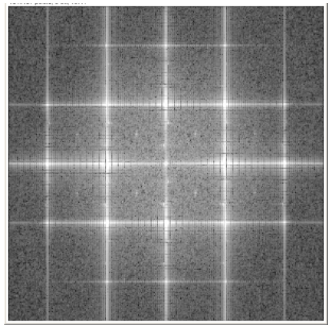


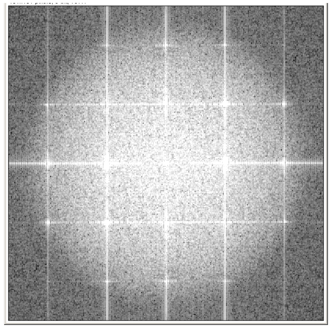
DUT image | 2D DTF - log | filtered DUT image | 2D DTF - log

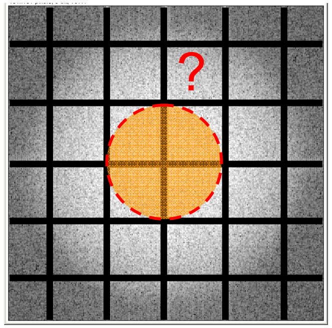
Sparkle in the Frequency Domain

T. W. Hsu, et al.: "Novel Evaluation Method of Sparkle ... ", IDW2014





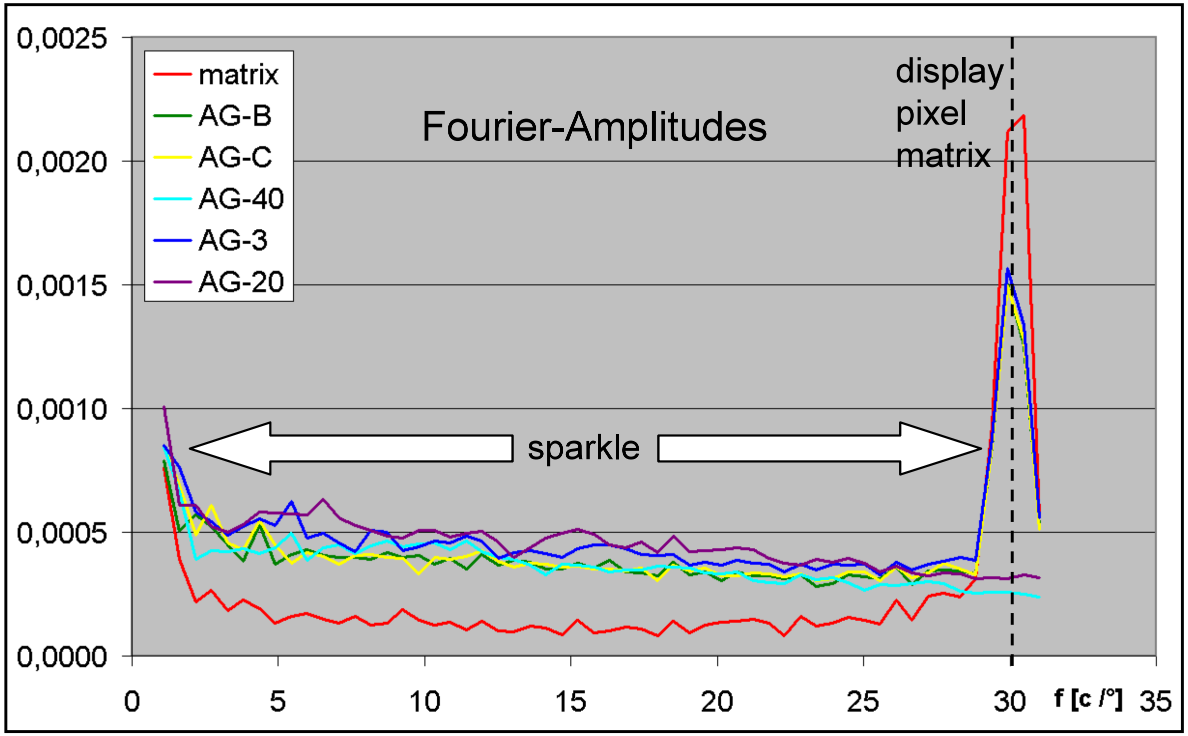




masking

"The sparkle parts can be estimated by ***summation of magnitude of spatial frequency domain without grid region***. Finally, the estimated value is divided by mean of each image to normalize the intensity difference from transmittance of AG films."

Sparkle in the Frequency Domain



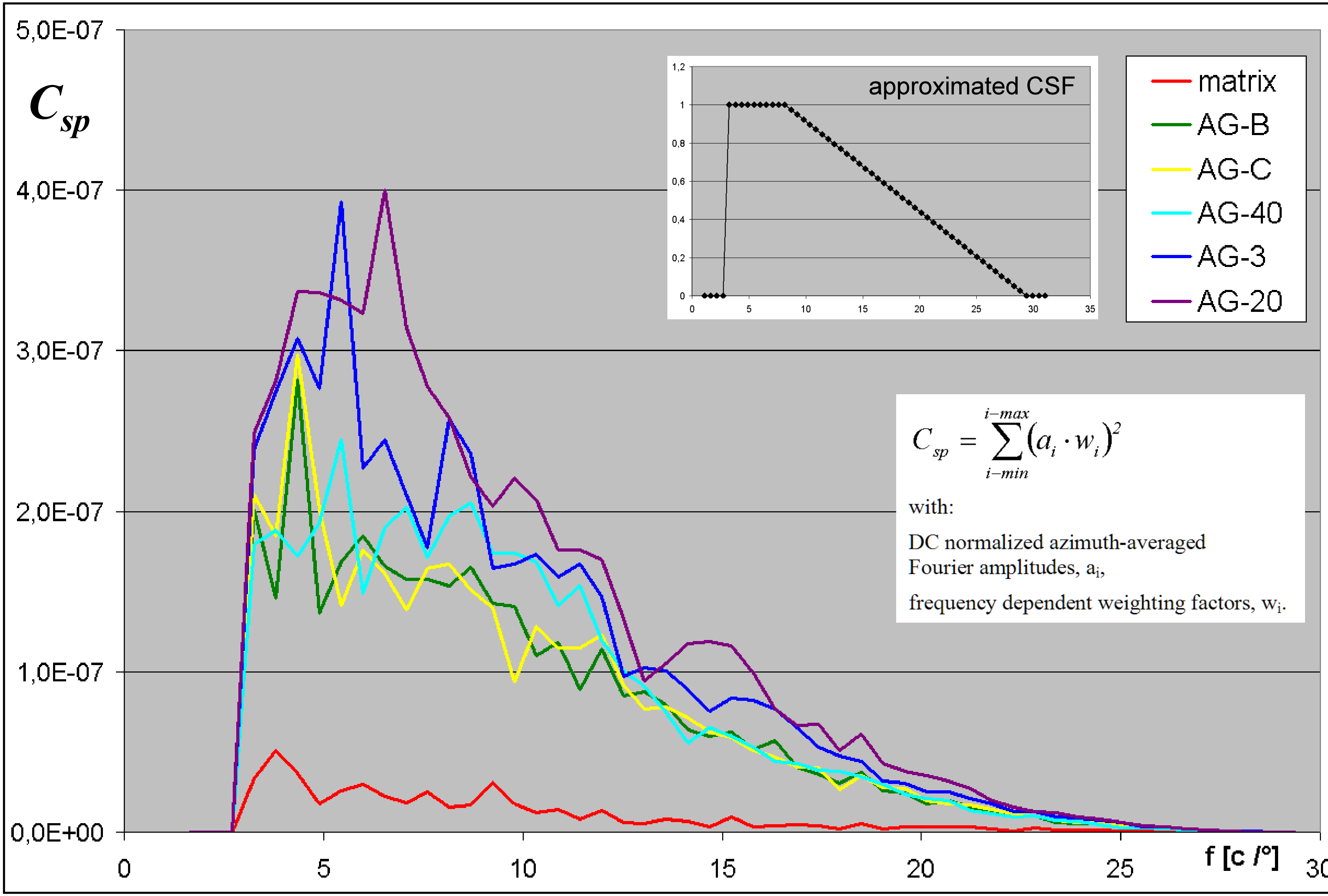
Weighting factors, w_i, are chosen in order to

(1) **approximate the human visual response** (e.g. maximum sensitivity between 3 c/° and 10 c/°, depending on details of the observation conditions (e.g. adaptation level), and

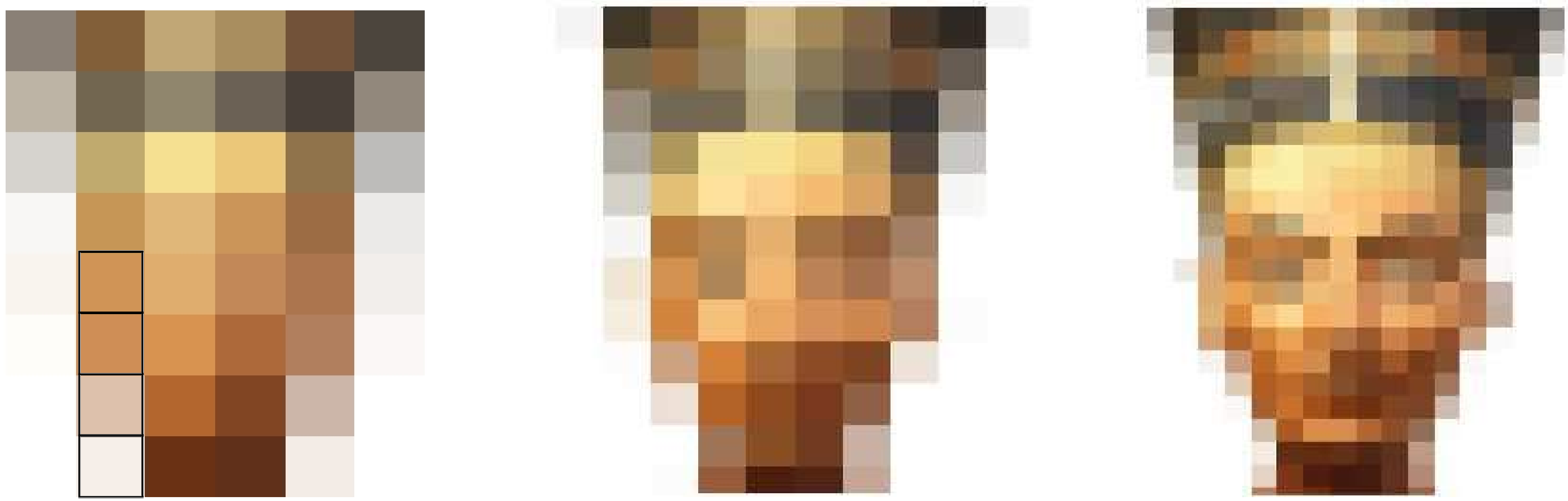
(2) to **suppress low frequency components** caused by non-uniformities of the backlight luminance, vignetting of the camera optics, etc. and

(3) to **remove all contributions from modulations at and above the fundamental frequency** (i.e. periodic modulation of the display pixel matrix) which cannot be perceived.

Sparkle in the Frequency Domain

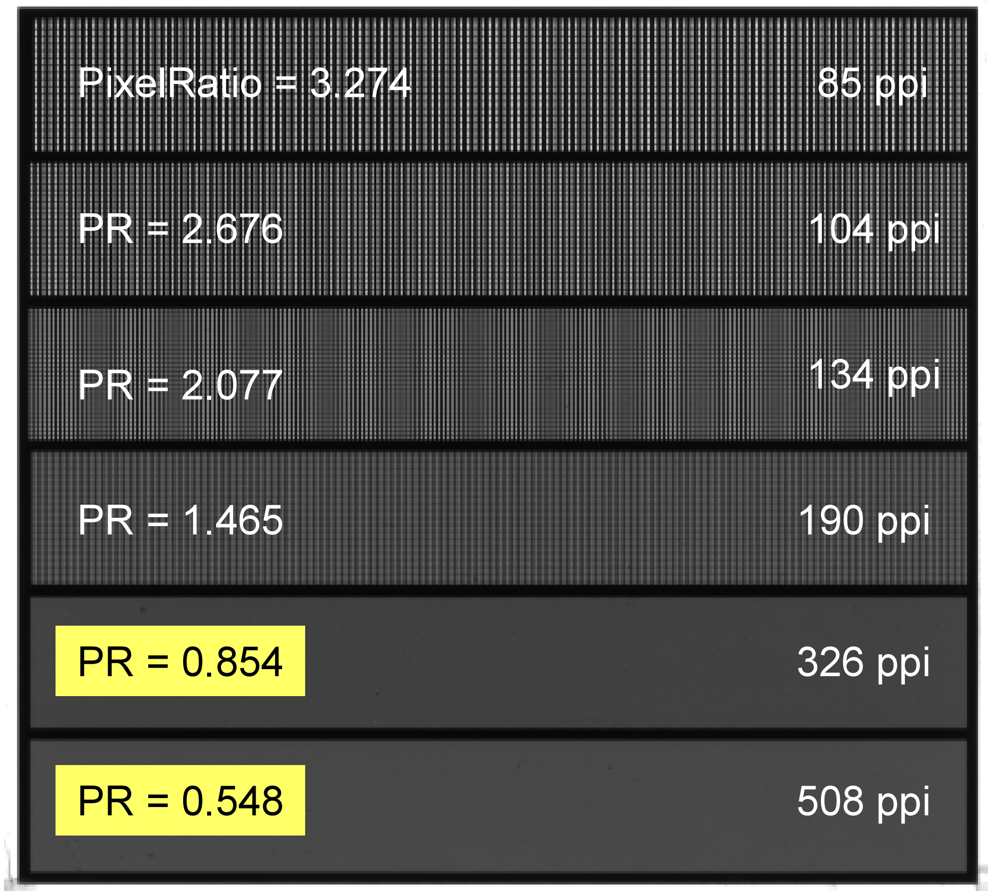


Undersampling of Object



M. Hayashi: "Simplified Method to Quantify Sparkling ... ", Proc. IDW2017

Undersampling of Displays



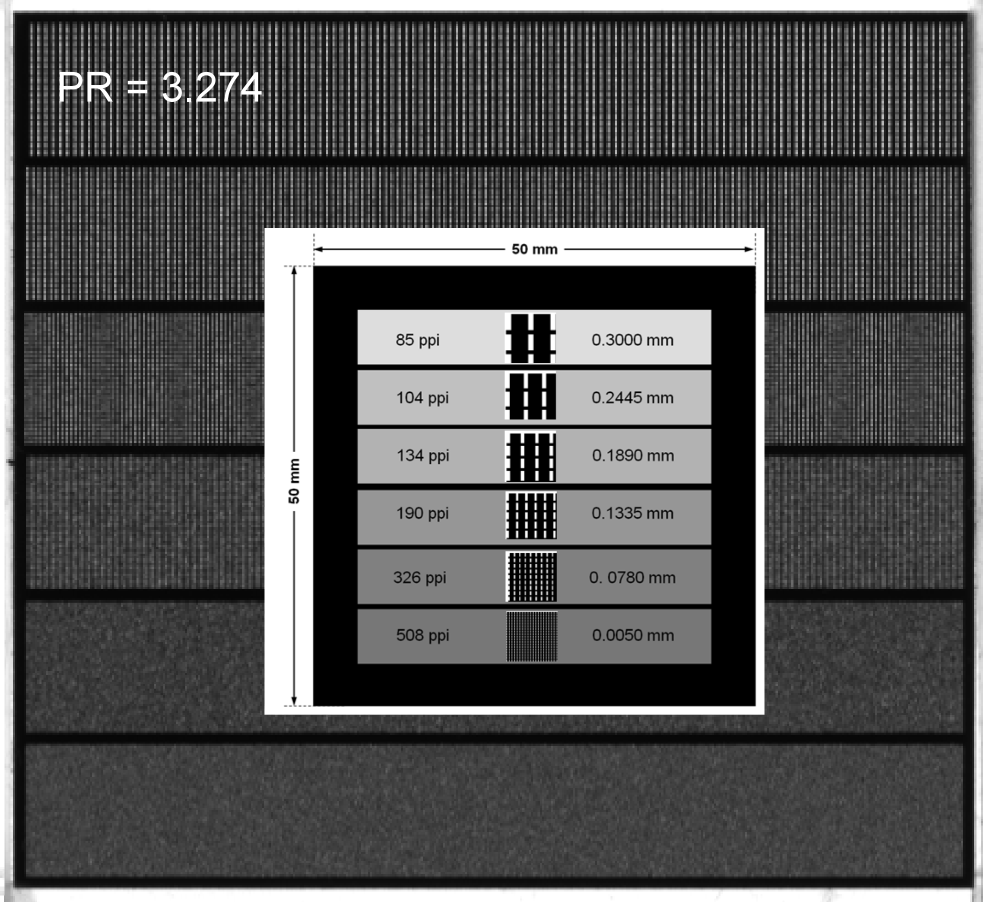
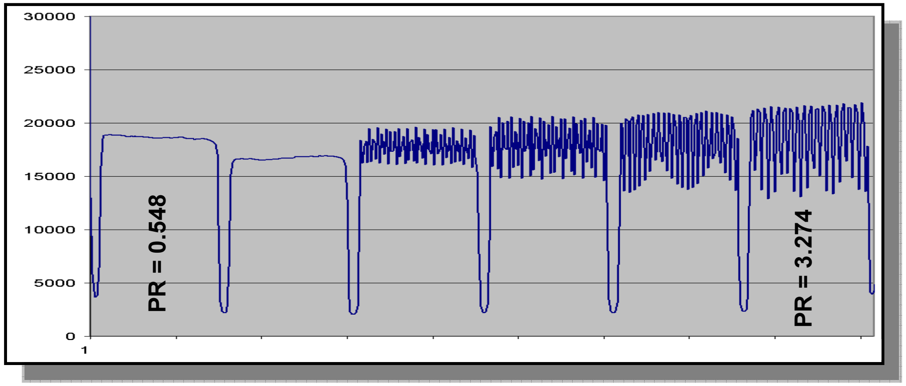
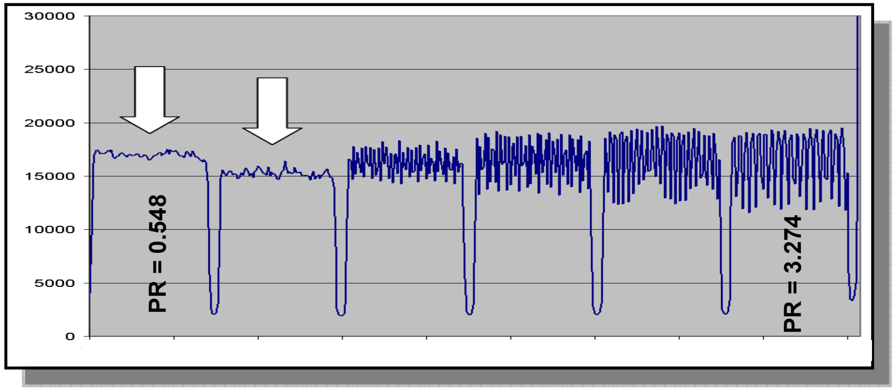


Image of the **bare pixel pattern matrix**

Image of **pixel pattern matrix + AG glass**



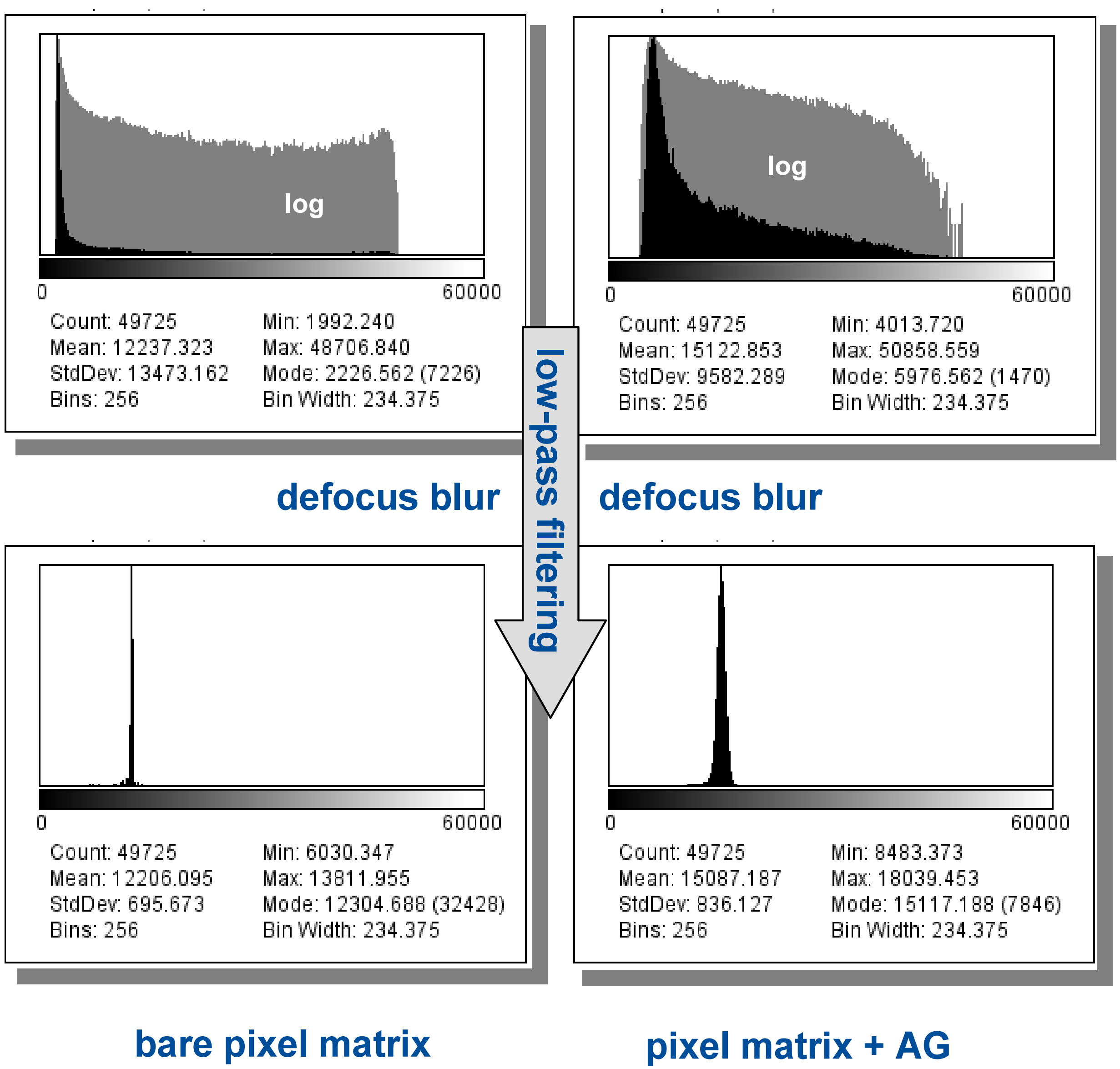


Histogram Analysis

V. Ferreras Paz: "Sparkle characterization ... ", Proc SID2018

- Adjustment of defocus-blur.
- Recording of blurred image.
- Calculation of histogram.
- Histogram fitting to Gaussian.
- σ / FWHM specify sparkle level.

In this illustrative example the blurred image of the DUT is obtained by applying Gaussian blur to a focused image.



Summary

➲ Sparkle evaluation is sensitive to a variety of parameters.

➲ **Sparkle rankings are easier to reproduce than absolute levels.**

➲ The imaging conditions shall be well specified,
comprising geometry, optics, complete system.

➲ Sparkle-bias is an important diagnostic for every method.

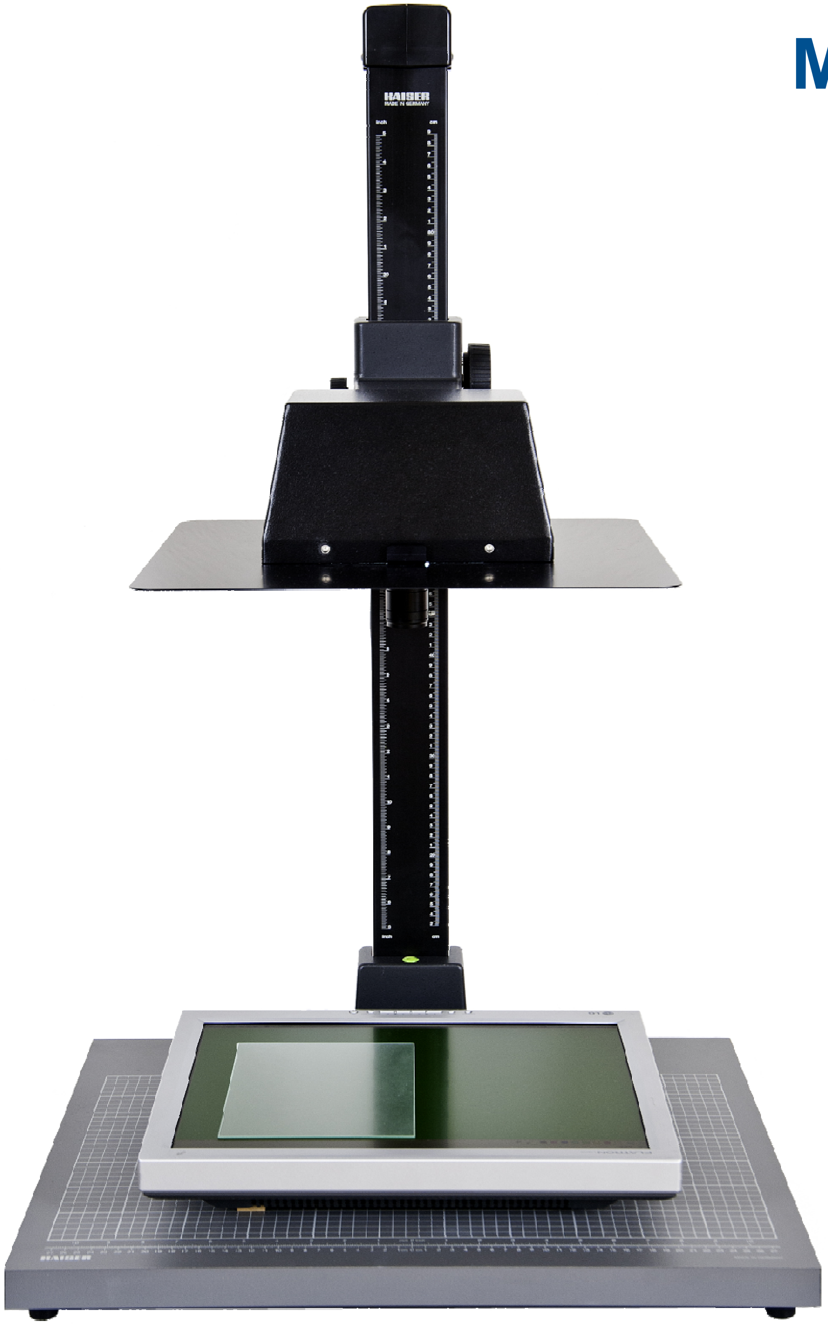
➲ Evaluation methods:

- spatial filtering,
- analysis in frequency domain,
- undersampling,

others ...

➲ Evaluation conditions, data processing, etc. shall be published.

➲ Two parties should agree on one method and one implementation to make results comparable.



Measurement and Evaluation of

- Sparkle (4 methods)
- Distinctness of Image (MTF)
- Transmittance Distribution
  - haze, clarity
- Reflectance Distribution
  - haze, clarity

- optional microscope head,
- features continuously expanded.

Sparkle related Publications

R. Adler, et al.: US Patent 4 972 117, 1990 sparkle = "*random moiré* "
AG-coatings for color CRTs

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
- C.R. Evans, et al.: "Method of measuring and quantifying sparkle ... ", J. Inf. Disp., 2014
- M. E. Becker: "Sparkle measurement revisited: a closer look at the details" Proc. SID2014, Journal SID 2015
- T. W. Hsu, et al.: "Novel Evaluation Method of Sparkle ... ", Proc. IDW2014
- M. E. Becker: "Sparkle Evaluation with Visual Weighting", Proc. SID2016
- M. Hayashi: "Simplified Method to Quantify Sparkling ... ", Proc. IDW2017
- V. Ferreras Paz: "Sparkle characterization ... with a grey value histogram analysis", Proc SID2018