electronicdisplays Conference DIGITAL

March 1. - 5., 2021

# 10 years of sparkle measurement - the lessons learnt

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**Abstract**

Measurement of ***display sparkle*** has become a routinely practiced method in a range of industries: display material and component producers, display integrators and system manufacturers, especially in the automotive displays supply-chain. In order to carry out measurements of sparkle in a reproducible way, the effect of the basic parameters of the measurement system (hard- and software) has to be thoroughly analyzed and understood as basis for control of the measurement and evaluation process and thus for well specified and repeatable measurement results..

**Keywords**
control of display reflections, anti-glare treatment, scattering AG-layers, display sparkle, imaging light measurement device (LMD), electronic imaging, image sampling and filtering

## 1. What is display sparkle ?

***Display sparkle*** is an unwanted, annoying ***pattern*** formed by a random arrangement of tiny dots visible across the display area that is changing its appearance (structure, luminance and chromaticity) with viewing direction in a pronounced way. It is just that variability with viewing direction that generates a visual impression of sparkling, glittering or twinkling.

While anti-glare treatments for color CRTs have been known and used latest since the 1960s (e.g. US patent 3,114.668, [1]), the terms *sparkle* and *sparkling* seem to be introduced by Robert Adler, et al., [2], US patent 4,972,117, Sparkle suppression displays, 1989, assigned to Zenith Electronics Corporation: "a disturbing phenomenon known as *sparkle* or *random moiré'* 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."

A more recent introduction into the optics and the visual perception of *sparkles* is provided by Alfred Cann in his article: "All about Sparkles", Optics & Photonics News, January 2013 [3]: "Because sparkles evade our depth-perception mechanism, ... they seem to float indeterminately rather than appearing on any surface or at any altitude. ... each sparkle is generally seen by only one eye, and thus the two eyes see different sets of sparkles. That prevents the depth perception system from fusing the two images and determining the distance to any one sparkle."

Display sparkle is generated by refraction of light when transmitted through a sandwich of two structured layers: the display pixel matrix (periodic structure) and the anti-glare (AG) layer comprising random micro surface structures (facets). Light transmitted by the (e.g. green) sub-pixels is re-directed by refraction induced by the micro-structures at the AG-layer surface (see e.g. [4]) as illustrated in Fig. 1.

Since introduction of the first instrumental realization for measurement and evaluation of display sparkle in 2011 [5] it has become a standard procedure in the process of optimizing display performance with respect to glare control and as a means of material and component specification in supply chains in the displays industry.

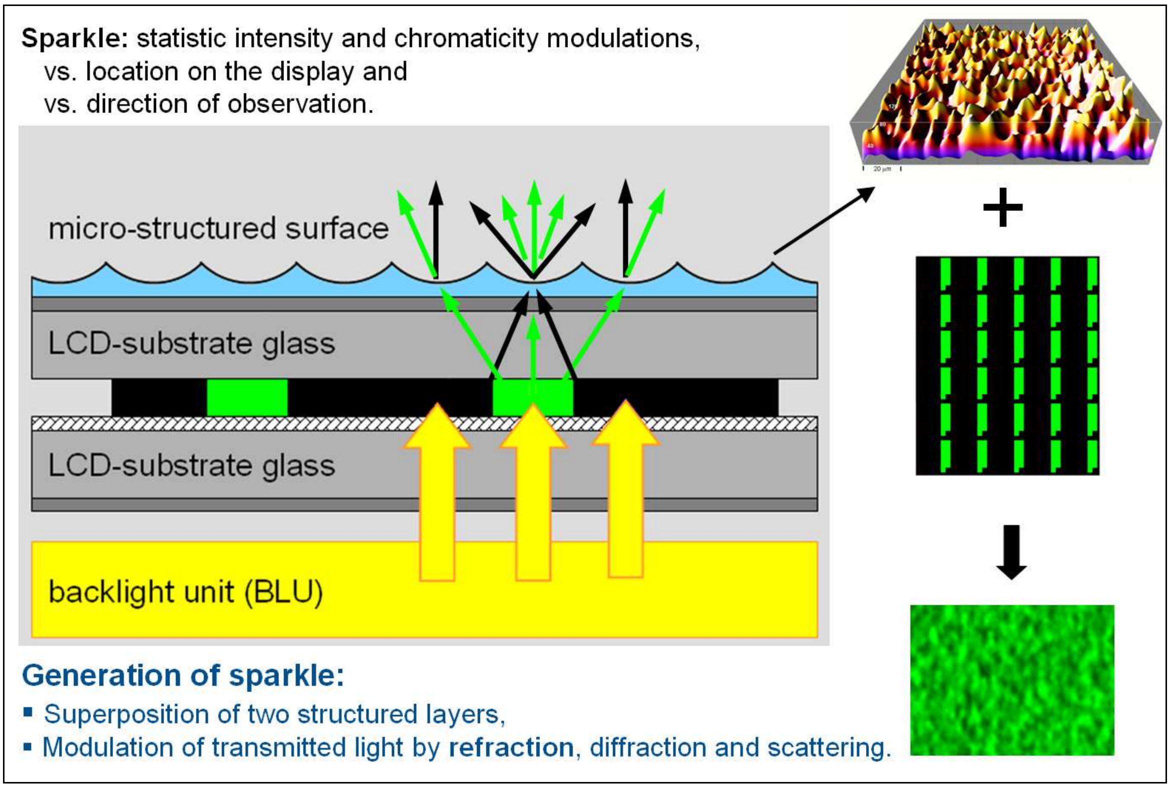


**Figure 1:** Generation of sparkle by refraction of transmitted light induced by the micro-structured surface of the anti-glare layer.

## 2. Conditions under which display sparkle is observed

A favorable observation situation for visual displays with regular subpixel arrangements is given when the viewing distance is chosen such that one elementary unit of the display (e.g. one pixel comprising RGB subpixels) subtends an angle of 1 minute of arc (1', observer with a visus of one). In that case the eye of the observer performs a spatial integration over that elementary cell (pixel) and no variations with higher spatial frequencies can be observed. The cut-off spatial frequency for an observer with visus of one thus is *30 cycles per degree* of visual angle.

We define a standard observation condition for sparkle such that one display pixel (or an elementary achromatic unit cell in the case of non-standard subpixel arrangements, e.g. PenTile layouts) subtends an angle of 1' which is considered to be equivalent to one detector element. For a display pixel pitch of 0.3 mm that means an observation distance of 1031 mm. A display with only green subpixels activated, when observed under that condition, is seen as a uniform green area (when other low-frequency intensity variations, e.g. backlight non-uniformity, are assumed to be zero), all random variations that can be noticed are due to sparkle. The cut-off frequency of the contrast sensitivity function (CSF) of the human eye thus separates lateral luminance variations perceived as sparkle from modulations with higher spatial frequencies, e.g. the details within one pixel as shown in Fig. 2 (see e.g. [6] and references therein). The aperture angle of the human eye ($\alpha$, Fig. 3) varies with state of adaptation (pupil diameter) and viewing distance (min. ~250 mm), it is in the range between 0.2° and 2°.

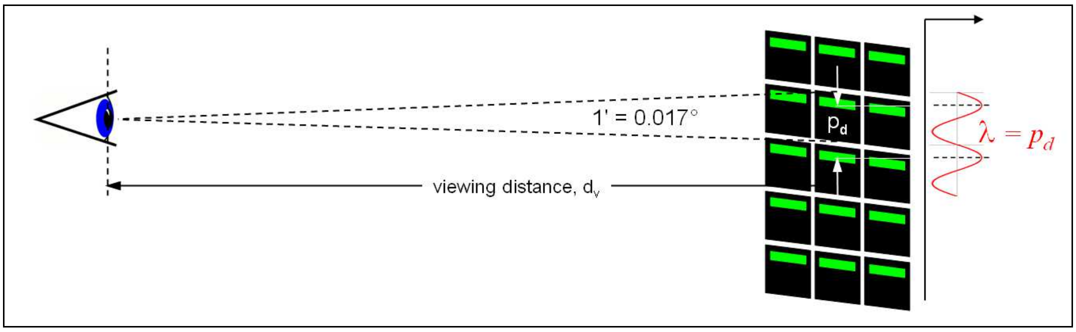


**Figure 2:** Visual integration over one display pixel, subpixels cannot be visually distinguished.

## 3. From observation to measurement

Measurement of sparkle starts with electronic imaging of the combination of a display and an anti-glare layer with an imaging light measurement device (LMD). The measured quantity can be the luminance or some integral over the visible spectral range of light.

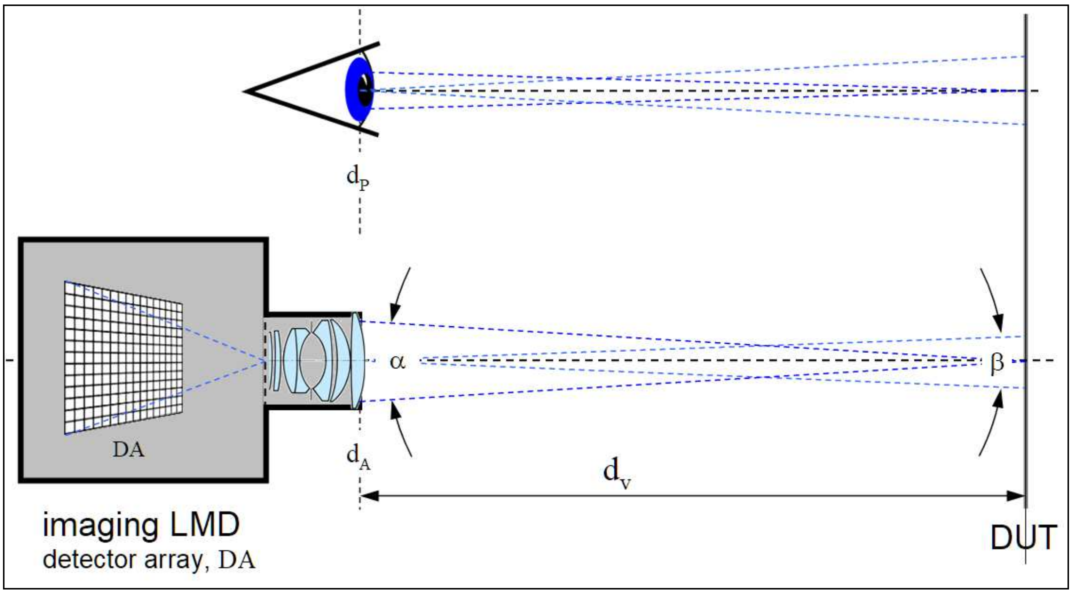


**Figure 3:** In the measurement setup the ***imaging LMD*** replaces the eye of the human observer. Since sparkle varies with direction of light propagation (observation), the angle subtended by the pupil of the eye and by the entrance pupil of the LMD are important parameters.

## 3.1. Electronic imaging of the display pixel matrix

A lens system usually images the display under test (DUT) on the 2D detector array of the LMD. The *modulation transfer function* (MTF) of the optical system has to be considered and the sampling of the DUT image by the detector array is of importance.

While in standard electronic imaging applications the object is usually oversampled (i.e. as many detector elements per element of the object image as possible), this is not the case when measuring display screens for sparkle evaluation as will be shown below.

When electronic images are taken from planar objects, for instance for reproduction of graphics and paintings, etc. the aperture of the objective lens is set to a size for which the MTF is optimum which means high spatial frequencies are not attenuated to assure reproduction of small object details. In the case of electronic imaging for sparkle evaluation however, sampling the display pixel matrix with the detector array may cause interferences (moiré) and aliasing which both may negatively affect the sparkle contrast levels obtained from the evaluation process.

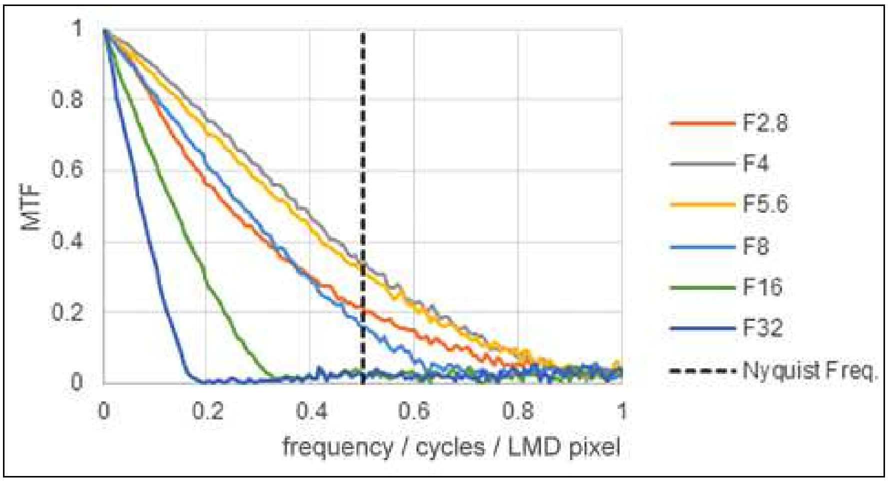


**Figure 4:** MTF as a function of the F# for a 50 mm objective lens used for sparkle measurements.
Courtesy of Dr. Kenichiro Masoaka

The level of sparkle is specified by a contrast, namely the quotient of standard deviation and average value of the random intensity variations (aka *speckle contrast,* $C_s = \sigma / \mu$) after removal of the periodic modulations induced by the display pixel matrix from the electronic image.

## 3.2. Sampling conditions

If the measurement setup is supposed to reproduce the observation conditions such that there is integration just over one display pixel (or equivalently one achromatic unit cell) to visually separate random sparkle modulations from periodic display pixel matrix modulations, the imaging of the LMD could be adjusted accordingly. Such an approach where the optical system of the LMD images one display pixel on one detector pixel had been described by Hayashi [7]. Even though the basic idea of this approach seems convincing, practical realization turns out to be difficult to impossible since even the slightest deviations of the ***image sampling rate*** (ISR, i.e. dimension of the image of one - square - display pixel divided by the dimension of one - square - detector pixel) from the target value of one (ISR = 1) introduce considerable errors in the sparkle contrast levels. Adjustment of the imaging condition may require additional scales or rulers preferably with a pitch that is an integer fraction of the display pitch.

The next *ISR* of interest would be two, but in the vicinity of the Nyquist sampling limit pronounced low-frequency modulations occur [8] that are negatively affecting evaluation of the sparkle contrast. With increasing ISR value above two the low-frequency modulations decrease and at about ISR = 2.4 the lower limit of usable sampling rates is reached. The three classes of sampling conditions are illustrated in Fig. 5 where one sample corresponds to one detector element.

The frequency components of an image recorded with an ISR of 5.39 is shown in the log-gray-scale image of Fig. 6. The frequency components of the display pixel matrix form a square grid with the basic frequency $f_0$ given by the ratio of detector pitch divided by the pitch of the display pixel image. The center of the diagram corresponds to the zero frequency (DC component) and the periphery of the square diagram corresponds to the Nyquist frequency of the detector array which is 1 cycle per two LMD detector pixels, $f_N$ = 1/2. The amplitude peak marked by the red arrow represents a frequency in the image that is above the Nyquist frequency and folded back into the baseband (mirroring about the Nyquist frequency). Such "aliased" frequency components contribute to the sparkle contrast and thus cause erroneous results. $f_0$ is given by the quotient of the display pixel image pitch devided by the detector pixel pitch.

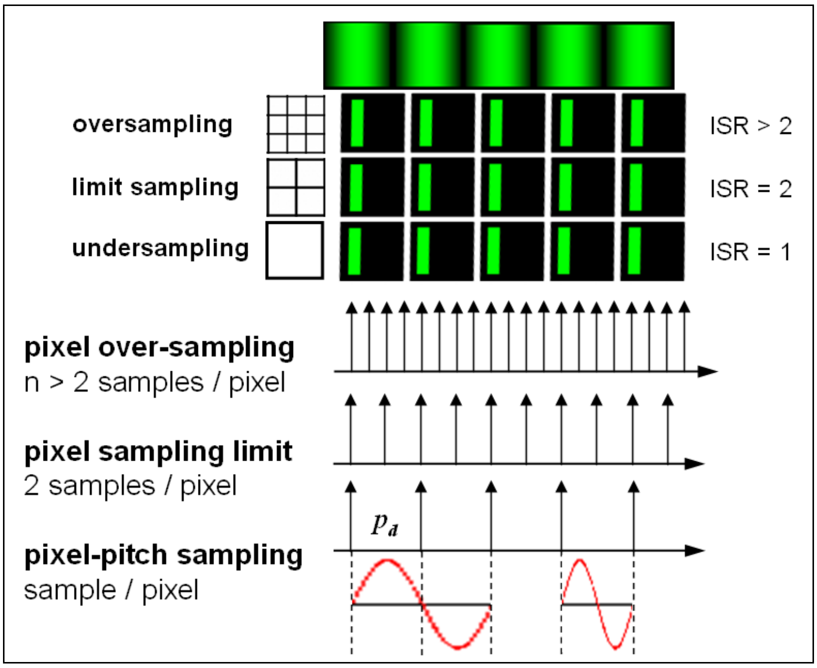


**Figure 5:** Three classes of conditions for sampling of a display pixel matrix by an array of detector elements: oversampling, sampling at the Nyquist limit and undersampling.

## 3.3. Separation of periodic and random modulations

In order to suppress the periodic frequency components caused by the display pixel matrix in the case of non-integer (i.e. fractional, rational) sampling rates, the electronic images acquired by the LMD can be filtered, either in the spatial domain by e.g. convolution with a rational kernel (i.e. a square kernel with rational dimensions, as introduced in [6]) or by filtering (masking) in the frequency domain [5]. In any case the level of sparkle contrast is calculated as described above ($C_s = \sigma / \mu$)) from the filtered electronic images.

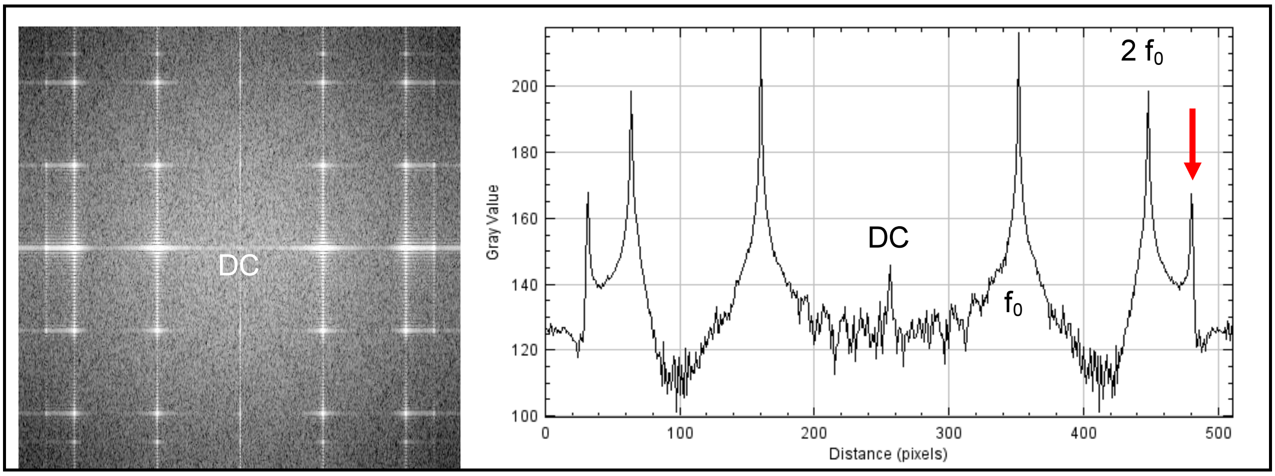


**Figure 6:** 2D discrete Fourier transform (log. amplitude, left) of the combination of a display pixel matrix and an AG-layer for different sampling conditions (ISR = 5.39), profile along the horizontal axis.

## 3.4. Frequency characteristics of filtering

Filtering of images in the spatial domain is often realized by convolution with suitable designed kernels, e.g. for edge detection, sharpening or blurring of image content. The dimensions of such kernels are usually odd integers and the result of one operation is assigned to the central image pixel. When the elements of the kernel are identical, application of such a convolution is also called "moving window averaging" or "box"-filtering. The frequency response of such filtering process is given by the sinc-function with the zeroes of the function corresponding the inverse of the width of the kernel dimensions [9].

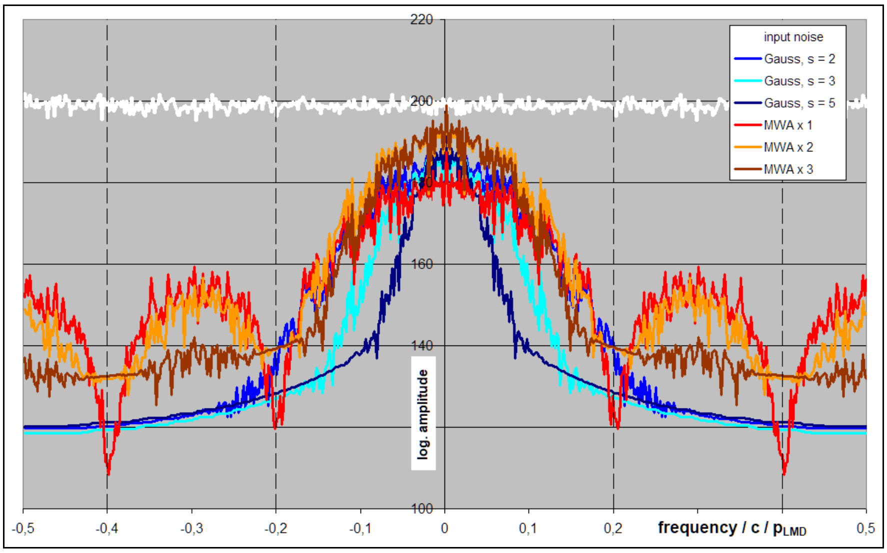


**Figure 7:** Comparison of normalized frequency responses of convolution with a *Gaussian* kernel (different standard deviations) and consecutive applications of a uniform kernel (*MWA*, width = 5).

The frequency responses of arbitrary convolution filters can be conveniently checked numerically as follows: images are created with a white noise dot-pattern and after application of the filter the 2D FT is evaluated as illustrated with the normalized profiles (i.e. logarithm of response amplitudes vs. frequency) of Fig. 7.

In the case of filtering in the frequency domain a mask is constructed by suitable processing steps from the 2D discrete Fourier transform of the image. That mask removes the unwanted frequency components before an inverse Fourier transform (FT) back into the spatial domain is performed.

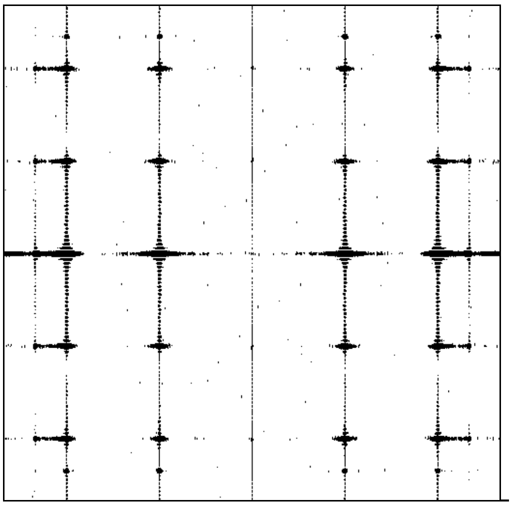

**Figure 8:** Example of a mask obtained form the 2D FT of Fig. 6 (left) for suppression of periodic modulations caused by the display pixel matrix.

The mask shown in Fig. 7 shows that its application does remove the periodic frequency components caused by the display pixel matrix (fundamental and harmonics), but it does not remove the components in between multiples of $f_0$. The same applies for application of the convolution filtering as illustrated in Fig. 7. In order to make sure that frequency components above the fundamental frequency of the display pixel matrix do not contribute to the evaluation of the sparkle contrast,. frequency components above $f_0$ should be removed from the images. That can be achieved by multiple application of the MWA filter (3 applications are sufficient) and by modification of the mask in frequency domain as illustrated in Fig. 9.

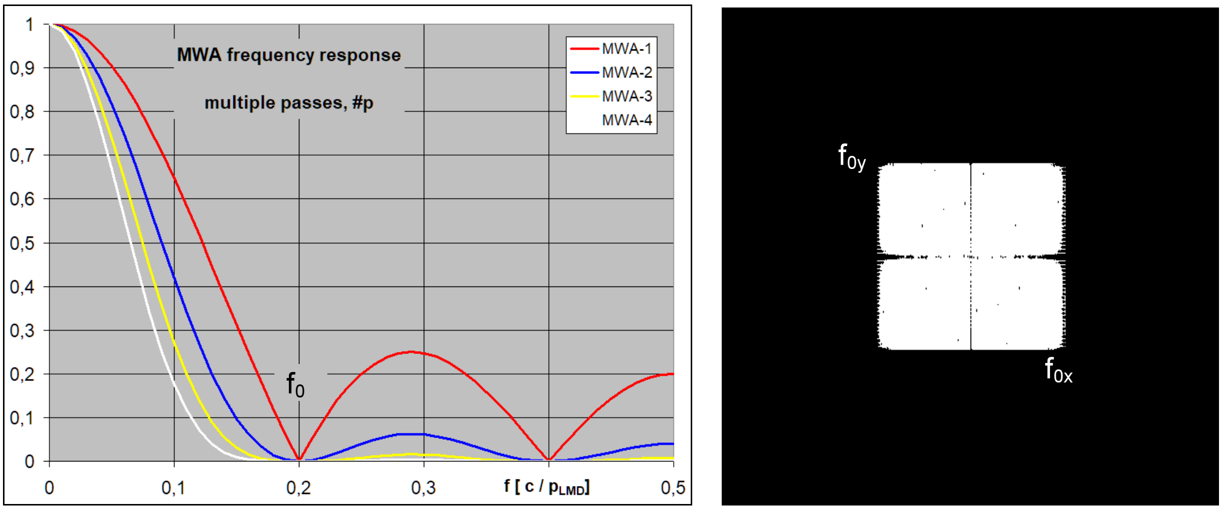


**Figure 9:** Frequency response of multiple applications of the MWA filter (convolution) and modification of the frequency filtering mask to exclude frequencies above $f_0$ from sparkle evaluation.

### 3.5. Down-sampling

Application of the MWA filtering process comprises two steps: first, the average intensity level of an area corresponding to one display pixel is calculated from the source image and assigned to the kernel center location in the target image. Then, the kernel is shifted by one source image pixel and the next averaging is performed. This procedure produces a target image with the same dimensions of the pixel array as the source image. A change of the translation of the kernel from one source image pixel to one display pixel width (i.e. by a factor of ISR, [10]) effects a down-sampling of the LMD image and thus cancelation of frequencies that do not contribute to the visual impression of sparkle according to the considerations in chapter 2.

### 3.6. Variation of sparkle with LMD aperture angle

Display sparkle is observed as a random arrangement of dots across the display area which (in the case of quasi-monochromatic illumination) exhibits a strong variation of structure (dot intensities and locations) with viewing direction. This fact has the following implications when the LMD lens aperture is varied: In the case of large apertures high frequency components are received and the image of the dot pattern is sharp. However, since the large aperture at the same time averages over a wide range of directions, intensity modulations within the lateral sparkle pattern are small, resulting in small sparkle contrast values as illustrated in Fig 10.. With decreasing lens aperture angle the resolution of the lateral dot pattern decreases, but the reduced directional averaging increases the intensity modulations within the pattern. As a consequence, sparkle contrast increases up to an aperture size where low-pass filter blurring takes over (compare the variation of lens MTF with F# shown in Fig. 4) and cannot be compensated by increased directional selectivity. As a consequence, the sparkle contrast decreases with increasing F#. For IRS values between 3 and 6 the maximum sparkle contrast is obtained for F#/8 for one specific AG sample. A more detailed analysis of the effect of LMD aperture angle on measured sparkle contrast and the correlation with expert visual ratings has been provided by Isshiki and colleagues [11]. Their results provide evidence that the maximum of sparkle contrast does not necessarily correspond to the best correlation of measured sparkle and visual rating.

## 4. Limits of sparkle evaluation

The ultimate reference for sparkle evaluation is the experience of the human eye, which however is varying considerably from person to person. Since visual rating of sparkle even by experts does not provide absolute values, sparkle inspection usually yields a ranking of a set of samples obtained by a multitude of pairwise comparisons.

The objective of measurement methods for sparkle evaluation thus is to reproduce the ranking as obtained by expert visual ratings. Even such a reduced requirement is not as easy to meet as it may sound since the visual appearance of sparkle may depend on the size of sparkle dots (granules), on the distance between them (lateral spatial frequencies) and on the "angular lifetime" which specifies the degree of variation of a sparkle dot's intensity with viewing direction.

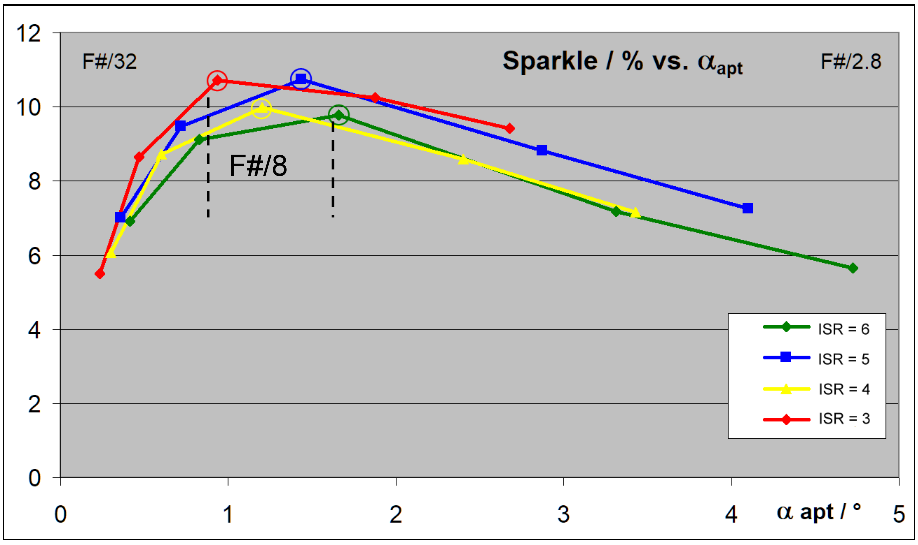


**Figure 10:** Variation of sparkle contrast with LMD aperture angle for different image sampling rates, IRS. For all IRS values the maximum sparkle contrast is obtained for F#/8 (encircled dots), with maximum levels in the range between 9.77 % and 10.74 %.

## 5. Conclusions

Unwanted sparkle in displays is - similar to intended sparkle in decorative paints and varnishes (see e.g. CIE JTC 12: *The measurement of sparkle and graininess*) - a complex optical and visual phenomenon which cannot be measured as simple as e.g. surface gloss (put meter on top, push button, get result).

➲ There is no unique ideal procedure for sparkle measurement and evaluation.

All parameters of the measurement setup (LMD and imaging conditions) are affecting the images on which the evaluations are based. All parameters of the calculations for evaluation of sparkle contrast are affecting the results. To make measurements reproducible all relevant parameters must be specified in the measurement report.

Here are some general recommendations:

- Optical low-pass filtering by small lens apertures should keep frequencies above the detector Nyquist frequency out of the LMD to avoid aliasing.
- ISR as small as possible to limit frequency content of image.
- ISR adjusted to keep moiré modulations under control.
- Separation of frequencies included in the evaluation (e.g. multiple MWA applications, w = $2/f_0$)

## 6. Literature references


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