IEC 62977-3-9

Edition 1.0 2023-06

INTERNATIONAL STANDARD

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Electronic displays –
Part 3-9: Evaluation of optical performance – Display sparkle contrast

IEC 62977-3-9:2023-06(en)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 31.120; 31.260

ISBN 978-2-8322-7063-9

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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ELECTRONIC DISPLAYS –

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Draft	Report on voting
110/1515/FDIS	110/1525/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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ELECTRONIC DISPLAYS –

Part 3-9: Evaluation of optical performance – Display sparkle contrast

1 Scope

This part of IEC 62977 specifies standard measurement conditions and methods for determining the sparkle contrast of direct-view displays which comprise display matrix elements to render real 2D images on a flat panel and an anti-glare layer. This document excludes measurement of sparkle, which is intentionally obtained by the specular reflection from reflecting flakes in coatings and paints.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, abbreviated terms and letter symbols

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

3.1 Terms and definitions

3.1.1
sparkle
visual phenomenon that becomes obvious as a random pattern extending across the display area formed by a distribution of tiny patches (granules, dots) with varying luminance and chromaticity (depending on the test pattern shown on the display) through the anti-glare layer of the display, resulting in a visually disturbing pattern that is distinctly changing with viewing direction

Note 1 to entry: In other fields, the term “sparkle” can refer to reflections from reflecting particles in effect coatings [1].

Note 2 to entry: Sparkle looks like “speckle” [2] in the field of laser displays (coherent or partially coherent light), however sparkle and speckle are different because the origins of both phenomena are quite different.

3.1.2
sparkle pattern
radiance distribution of sparkle

Note 1 to entry: The sparkle pattern can contain (1) periodic modulations caused by the display pixel matrix, (2) non-periodic effects caused by, for example, pixel defects, and (3) low-frequency radiance variations caused by non-uniformities of the backlight unit.

3.1.3
sparkle contrast
S_P
quotient of the standard deviation of the radiance variation of the sparkle pattern in the measurement field divided by its mean (average) value

3.1.4
anti-glare layer
AGL
scattering layer for the suppression of distinct (mirror) images of ambient light sources reflected by smooth polished (display) surfaces

3.1.5
image sampling ratio
ISR
ratio of the pitch of display matrix elements multiplied by the magnification of the imaging lens to the pitch of the elements of the detector array

Note 1 to entry: For the details, see Annex A.

Note 2 to entry: The display matrix element refers to a physical sub-pixel in the display products. In the display mock-up, it means a fundamental element partitioned by the black matrix.

3.2 Abbreviated terms

A/D	analog/digital
AGL	anti-glare layer
CCD	charge coupled device
CMOS	complementary metal oxide semiconductor
DUT	device under test
ISR	image sampling ratio
LMD	light measuring device
MWA	moving window averaging
MTF	modulation transfer function
PPD	pixel power deviation

3.3 Letter symbols

The letter symbols are shown in Table 1.

Table 1 – Letter symbols (quantity symbols and units)

Quantities	Symbols and units	
Fundamental frequency of the periodic modulation of the display matrix image	f_0	(lp/mm)
Measurement distance	L	(mm)
F-number (infinity)	$F\#$	(-)
Effective F-number	$F\#_E$	(-)
Focal length	f	(mm)
Image distance	Z_L	(mm)
Optical magnification	m	(-)
Image sampling ratio (ISR)	R_S	(-)
Diameter of the airy disk of the LMD lens as projected on the DUT	S	(µm)

Quantities	Symbols and units	
Pitch of the image of the display matrix elements	P_D	(µm)
Dominant wavelength of the primary colour of the display	λ	(µm)
Standard deviation of the radiance variation of the sparkle pattern	σ	(W/sr/m^2)
Mean radiance of the sparkle pattern	μ	(W/sr/m^2)
Sparkle contrast	S_P	(-)
Radiance matrix representing the image of the DUT	$L(x, y)$	(-)
Square convolution kernel	$K(s, t)$	(-)
Radiance matrix representing the filtered DUT image	$L^*(x, y)$	(-)
Variables used during convolution	s, t	(-)
Number of LMD pixels in the square kernel per side given by the square of the closest odd integer	k	(-)
Sum of all weights used in the convolution matrix	S_W	(-)
Standard deviation of the radiance variation of the sparkle pattern from the image 1 which is used for the difference image method	σ_1	(W/sr/m^2)
Standard deviation of the radiance variation of the sparkle pattern from the image 2 which is used for the difference image method	σ_2	(W/sr/m^2)
Standard deviation of the radiance variation of the difference image	σ_{diff}	(W/sr/m^2)
Average background radiance used for the PPD calculation	bg	(W/sr/m^2)
Average sample radiance within the pixel bin with coordinates i and j, which is used for the PPD calculation	T_{ij}	(W/sr/m^2)
Average normalized sample radiance within the pixel bin with coordinates i and j, which is used for the PPD calculation	nT_{ij}	(W/sr/m^2)
Average normalized sample radiance over all element bins contained within area A, which is used for the PPD calculation	$\overline{nT_{ij}}$	(W/sr/m^2)
Average reference radiance within the element bin with coordinates i and j, which is used for the PPD calculation	R_{ij}	(W/sr/m^2)
Horizontal dimension in units of elements of area A which is used for the PPD calculation	u	(-)
Vertical dimension in units of elements of area A which is used for the PPD calculation	v	(-)
Number of segments per side used for the elimination method of the low-frequency radiance variations from the sparkle pattern	P	(-)
Number of LMD pixels per side in the segment used for the elimination method of the low-frequency radiance variations from the sparkle pattern	Q	(-)

NOTE 1 L is a distance from the DUT to the principal point of the imaging lens along with the optical axis. The principal point of the imaging lens can be determined experimentally by the method in section 17.5 of [3][1].

NOTE 2 Z_L is a distance from the principal point to the image point of the imaging lens along with the optical axis.

1 Numbers in square brackets refer to the Bibliography.

4 Standard measurement conditions

4.1 Environmental conditions

Measurements shall be carried out under the standard environmental conditions:

– temperature: 25 °C ± 3 °C,
– relative humidity: 25 % to 85 % RH,
– atmospheric pressure: 86 kPa to 106 kPa.

When different environmental conditions are used, they shall be noted in the measurement report.

4.2 Dark room conditions

The luminance contribution from ambient illumination reflected off the display shall be less than 1/20 of the lowest black level of the display. In the case of other dark room conditions, these shall be reported.

4.3 Warm-up time

The measurements shall be carried out after the DUT radiance and LMD are sufficiently stable. The radiance shall not vary by more than ±5 % over the entire measurement.

4.4 Measurement coordinate systems

The viewing direction is the direction under which the observer gazes at the point of interest on the device under test (DUT). During the measurement, the imaging light measurement device (LMD) simulates the observer, by aiming the LMD at the location of interest on the DUT from the viewing direction. The viewing direction is defined by two spherical angles: the angle of inclination θ (relative to the surface normal of the DUT) and the angle of rotation ϕ (also called azimuthal angle) as illustrated in Figure 1. Although the azimuthal angle is measured in the counter-clockwise direction, it is related to the directions on a clock face as follows: ϕ = 0° is the 3-o'clock direction ("right"), ϕ = 90° is the 12-o'clock direction ("top"), ϕ = 180° the 9-o'clock direction ("left") and ϕ = 270° the 6-o'clock direction ("bottom").

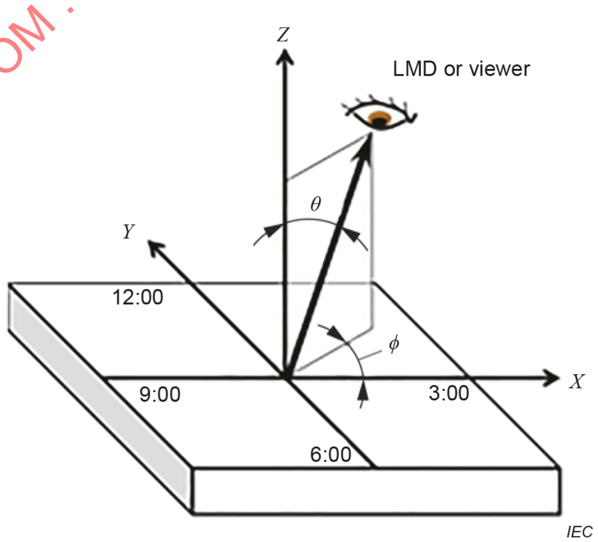


Figure 1 – Cartesian coordinate system and spherical coordinate system for the specification of the viewer's gazing (viewing) direction

4.5 Standard conditions for the measuring equipment

4.5.1 General

Measurement and evaluation of sparkle contrast can be performed during several stages of display manufacturing and use. Table 2 gives the explanation of the structure of this document, including the different measurements and their mutual relations. Combination of the display and the anti-glare layer (AGL) is the measurement subject of this document. The main body of this document only includes the typical measurement method which is commonly used for the measurements of sparkle contrast. For the cases when the image of the display matrix elements appears on the sparkle pattern, image filtering methods can be applied (see Annex B for examples of filtering methods). Annex F specifies a sparkle measurement technique that incorporates filtering after the images have been collected. Depending on the measurement conditions, the image of the display matrix elements, or moiré pattern (sampling artefact, see Annex A) can appear on the sparkle pattern. There are also cases where the image of the display matrix is not shown on the captured image because of the low modulation transfer function (MTF) condition of the imaging LMD (see Annex A).

During product development and optimization, the AGL (on a glass substrate or integrated into or applied to polymer films) is usually available as a separate component. In this case, there are two methods which can separate the random radiance variations that constitute sparkle from the low-frequency radiance variations caused by the non-uniformity of the backlight by using two different images. One is the difference image method in Annex E, the other is the pixel power deviation in Annex F. These methods are intended to investigate the performance of the AGL components under the fixed pitch of the display matrix elements. In the case where only the performance of the AGL components is investigated, a display mock-up can be used instead of intact displays. The details are introduced in Annex D.

NOTE The low-frequency radiance variations caused by the non-uniformity of the backlight can be removed by the methods in Annex G, when the DUT is an inseparable combination of the display and the AGL.

Table 2 – Distinguishing types of DUT, imaging conditions, number of involved images and methods for suppression of display matrix modulations

DUT	Imaging	Number and nature of images	suppression of display matrix modulation
Inseparable combination of display and AGL	Wide-band	Image number 1: sparkle pattern with display matrix modulation	Image filtering in spatial domain – MWA (B.2.1) Image filtering in frequency domain (B.2.2)
	Low-pass (Annex A)	Image number 1: sparkle pattern without display matrix modulation	No need for filtering applied to the image (Annex A).
Separate AGL + intact display Separate AGL + display mock-up (Annex D)	Wide-band	Image number 1: sparkle pattern with display matrix modulation	Image filtering in spatial domain – MWA (B.2.1) Image filtering in frequency domain (B.2.2)
		Image number 1: sparkle pattern with display matrix modulation Image number 2: sparkle pattern with display matrix modulation	Difference image method (Annex E) (with the methods in Annex B, if necessary)
		Image number 1: sparkle pattern with display matrix modulation Image number 2: display matrix image	PPD (Annex F)
	Low-pass (Annex A)	Image number 1: sparkle pattern without display matrix modulation	No need for filtering applied to the image (Annex A).

The configuration and the status of the components as agreed by the involved parties have to be specified in the measurement report.

Standard equipment conditions are given in 4.5.2. Any deviations from these conditions shall be noted in the report.

4.5.2 Conditions of measuring equipment

The sparkle contrast shall be measured using the standard measurement conditions given in 4.1, 4.2, and 4.3. The LMD shall be used within the effective range of measured radiance in terms of linearity.

An imaging LMD comprised of imaging optics (e.g., objective lens) and an array of opto-electronic detector elements with a spectral sensitivity covering the visible wavelength range (e.g., 380 nm to 780 nm) as used in black and white cameras (e.g., CCD or CMOS technology) is used for measurement of the sparkle contrast. Figure 2 shows a typical relative spectral response of a CCD detector array without IR-blocking filter (B/W camera) and a luminance meter with a sensitivity according to CIE $V(\lambda)$. Basic LMD aspects like linearity between light input and output signal, flat-field correction, dark signal compensation, etc., should be specified according to the state-of-the-art (see e.g., [4], [5]).

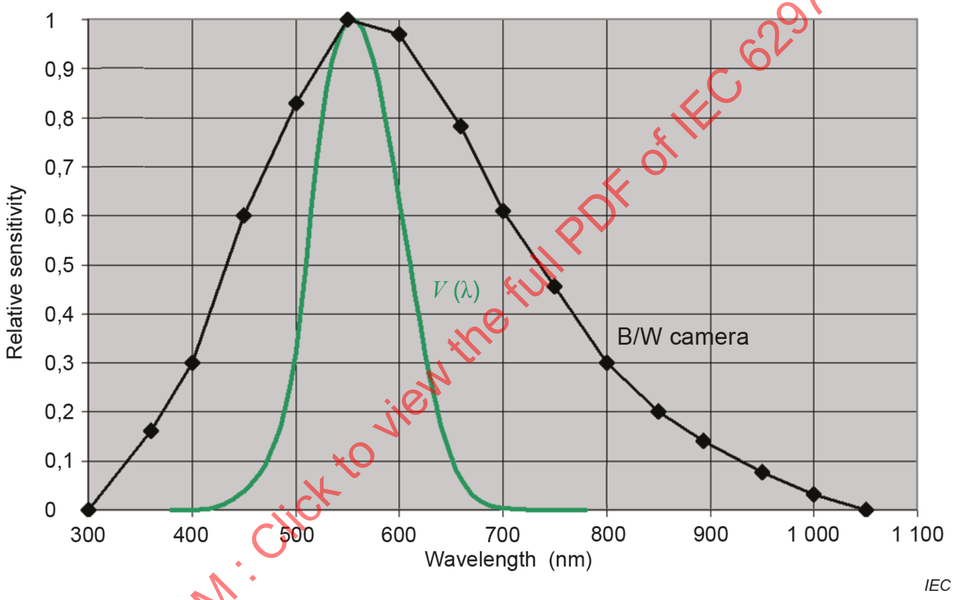


Figure 2 – Typical relative spectral response of a CCD detector array without IR-blocking filter (B/W camera) and a luminance meter with a sensitivity according to CIE $V(\lambda)$

The following conditions and settings of the sparkle contrast measuring equipment shall be noted in the report:

a) measurement distance: L,

b) viewing direction,

c) size of the measurement field

   1) optical system parameters of the imaging LMD;

   2) imaging lens F-number (infinity): $F\#$;

   3) focal length of the imaging lens: f;

   4) image sampling ratio: R_S;

d) specifications of the imaging LMD

   1) pixel size and pitch;

   2) bit depth;

   3) exposure time.

NOTE 1 As a measurement distance, the distance from the DUT to the specific reference plane of the LMD can be reported. In such a case, it cannot be used as a measurement distance L in Formula (1).

NOTE 2 An imaging LMD which has spectral responsivity of $V(\lambda)$ can be used.

NOTE 3 In the context of this document, the imaging LMD has a spectral sensitivity covering the visible range of electro-magnetic radiation (i.e. 380 nm to 780 nm).

NOTE 4 Only the primary colour is measured.

NOTE 5 The statistical error of the sparkle contrast is dependent on the size of the measurement field (the size of the evaluation region in LMD pixels) [6].

NOTE 6 The maximal resolution of a sparkle contrast measurement result can be affected by the digitization error of the A/D (analog/digital) conversion of the imaging LMD.

NOTE 7 The effective resolution of a sparkle contrast measurement result depends on the number of bits and the signal-to-noise ratio of the measurement, which is affected by the capturing conditions, for example exposure time.

For the comparison of the measured sparkle contrast, the diameter of the airy disk of the LMD lens as projected on the DUT, S, shall be the same [7]. S is proportional to the ratio of the effective imaging F-number, $F\#_E$, to the optical magnification, m, as shown in Formula (1), when the LMD focus is on the display matrix. m can be expressed as the ratio of the image distance: Z_L to the measurement distance: L,

$$S \propto \frac{F\#_E}{m} = F\#_E \frac{L}{Z_L} \tag{1}$$

In other words, S is inversely proportional to the numerical aperture of the imaging lens. It is necessary to use the same angular aperture for the comparison of the sparkle contrast. Furthermore, the same $F\#_E$ and the same LMD pixel pitch are also required for the comparison of the sparkle contrast [7].

NOTE 8 The setting error of the lens aperture (i.e. imaging F-number) can affect the MTF of the imaging lens, which results in a different sparkle contrast value.

All the conditions shall remain unchanged through the whole series of measurements, because sparkle contrast can be sensitive to each of the listed parameters (an example of how $F\#_E$ affects the MTF is shown in Annex C).

4.5.3 Standard measurement locations

Measurements shall be taken at the centre of the active display area of the DUT. If the measurements are taken at other locations, those locations shall be specified in the report.

4.6 Test pattern

The pattern shall be either full screen or sufficiently large (to be specified and reported) and a uniform field at the maximum either R, G or B input signal level. The RGB signal value shall be noted in the measurement report. In addition, the measurement field in which the evaluation is carried out shall be reported. The measurement field being evaluated should be large enough to cover a sufficient number of display matrix elements (e.g., over 100) but not too large to keep the effect of long-period radiance variations as small as possible.

5 Measurement methods

5.1 Purpose

The purpose of this method is to measure the sparkle contrast of direct-view displays which include AGL on surfaces.

NOTE In case display mock-ups are used instead of actual displays to optimize the anti-glare performance of the anti-glare layer, see Annex D.

5.2 Equipment and conditions

The measurement shall be as follows:

1) Imaging LMD as described in 4.5.2.
2) Measurement setup: The imaging LMD shall be aligned perpendicularly to the DUT surface as shown in Figure 3. The dimensions and location of the measurement field have to be specified with the DUT centre as the default location. The setup should be rigid and stable in order to avoid displacements and vibrations during image acquisition, which can severely distort the recorded images and thus affect the results.

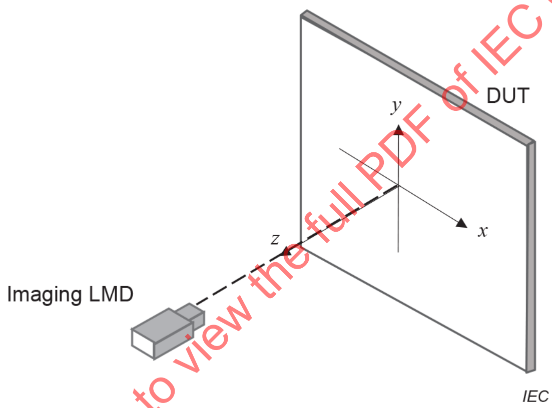


Figure 3 – Measurement setup

5.3 Measurement procedure

The measurement procedure shall be as follows:

1) Position and align the DUT and LMD according to Figure 3. Orientation of the LMD perpendicularly to the DUT surface is the preferred orientation (see 4.5.2), since all other orientations (e.g., inclination angle ≥ 2°) would introduce a variation of spatial frequencies across the recorded image and thus negatively affect the basis for further evaluation.
2) Allow sufficient time for the DUT and LMD to thermally stabilize. Sufficient warm-up time has been achieved when the radiance of the test feature to be measured varies by less than ±5 % over the entire measurement period (e.g., uniformity measurements) for a given display test pattern.
3) Correct the rotational mismatch physically between the LMD and the DUT: the display matrix elements have to be parallel or perpendicular to the LMD sensor pixel matrix.
4) Focus the LMD on the display matrix elements of the DUT. Be aware that incorrect focusing can act as an optical low-pass filter and thus affect the sparkle evaluation.

   NOTE Depending on the setup used for sparkle measurement, a limited depth of focus (i.e., in case of large aperture angle) can reduce the reproducibility of manual focus lenses. Fine tuning of the focusing can be done by slightly scanning the working distance of the LMD in search of the maximum value of sparkle contrast [8].

5) Capture the image without overflow of the detector array of the imaging LMD.

5.4 Calculation

Calculate the sparkle contrast S_P in the measurement field. This is achieved by calculation of the mean radiance value in the measurement field μ and the standard deviation of recorded radiance variations within the measurement field σ with the following formula:

$$S_P = \frac{\sigma}{\mu} \tag{2}$$

5.5 Report

Report the sparkle contrast together with the complete set of parameters that describe the imaging and evaluation process.

Annex A
(informative)

Imaging and sampling conditions of sparkle pattern

A.1 Oversampling

Oversampling is a condition when the ISR is over 2 (refer to [8] to [12]). In the case that the imaging condition is oversampling and the periodic structure of the display matrix is shown on the captured image, it can be eliminated by the spatial or frequency filtering methods (see Annex B). Even if the measurement condition is oversampling, there are cases where the image of the display matrix is not shown on the captured image because of low MTF condition of the imaging LMD when the condition of Formula (A.1) is satisfied [9],

$$\frac{F\#_{\mathrm{E}}\,\lambda}{P_{\mathrm{D}}} \geq 1{,}25 \qquad \text{(A.1)}$$

where

P_{D} is the pitch of the image of the display matrix elements on the LMD sensor;

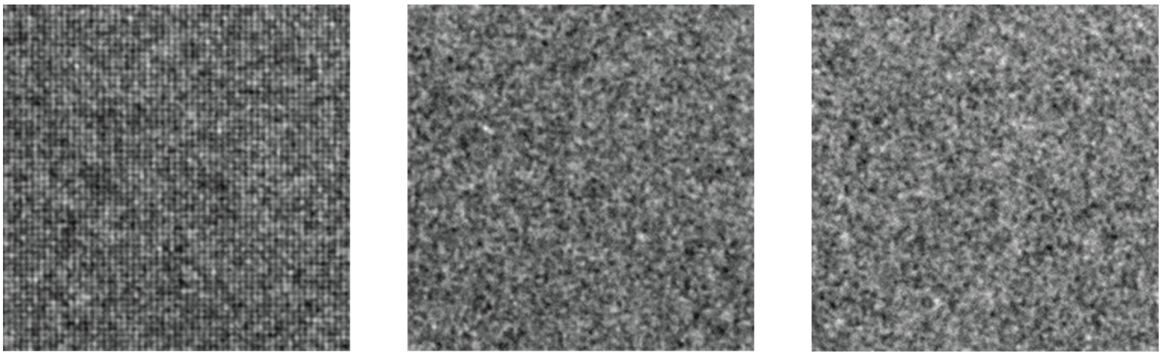
λ is the dominant wavelength of the primary colour of the display used in the measurement.

Formula (A.1) is a condition in which the radiance modulation of the image of the display matrix elements optically disappears on the LMD sensor plane, thus it can be applicable to the various LMD pixel pitches without generating moiré effect (a sampling artefact) caused by the combination of the pitches between the image of the display matrix elements and the LMD pixels. Figure A.1 shows examples of sparkle images from the same DUT under the different measurement distances with an LMD pixel pitch of 5,5 µm. Related measurement parameters are listed under each image. Periodic radiance variations derived from the display matrix elements were measured on the sparkle pattern in Figure A.1(a), while they disappeared in Figure A.1(b) and Figure A.1(c). In the case when the condition of Formula (A.1) cannot be satisfied and the imaging conditions is oversampling, the periodic radiance variations derived from the image of the display matrix elements can be separated from the sparkle pattern by the filtering methods in Annex B or Annex F.

NOTE 1 Moiré pattern cannot be perfectly removed by the filtering methods when the ISR is not an integer.

NOTE 2 Aliasing caused by sampling of the image of the display matrix elements can be avoided by satisfying the condition of Formula (A.1).

NOTE 3 Smaller lens aperture settings or larger measurement distances can reduce or eventually suppress the statistical radiance variations that constitute sparkle in the measured images.



(a)

$$\frac{F\#_E \lambda}{P_D} = 1{,}00$$

L = 400 mm, Z_L = 70,6 mm,
$F\#_E$ = 37,6, P_D = 20,6 µm,
R_S = 3,75, λ = 0,547 µm

(b)

$$\frac{F\#_E \lambda}{P_D} = 1{,}25$$

L = 500 mm, Z_L = 68,2 mm,
$F\#_E$ = 36,4, P_D = 15,9 µm,
R_S = 2,89, λ = 0,547 µm

(c)

$$\frac{F\#_E \lambda}{P_D} = 1{,}50$$

L = 600 mm, Z_L = 66,7 mm,
$F\#_E$ = 35,6, P_D = 13,0 µm,
R_S = 2,36, λ = 0,547 µm

Figure A.1 – Examples of sparkle image from the same DUT under different measurement distances

A.2 Undersampling

Undersampling is a sampling condition when the ISR is below 2. Under this condition, the original periodic structure of the display matrix cannot be reproduced by the captured image [10].

NOTE When the condition of Formula (A.1) is not satisfied, various forms of aliasing occur. For an ISR close to 2, strong low-frequency modulations appear on the image.

Annex B
(informative)

Filtering methods for removing periodic modulations from the image

B.1 General

The sparkle pattern, i.e., the statistical variation of radiance across the display surface, is superimposed on the periodic structure of the display matrix elements. For evaluation of the sparkle level (i.e., the value of the sparkle contrast) it is thus required to separate the random variations that constitute sparkle from the regular periodic variations caused by the display matrix elements as well as non-regular static variations (e.g., defect pixels, damage, non-uniformities of the backlight). Such a separation can be achieved by spatial filtering (e.g., low-pass filtering with a 2D moving window averaging (MWA) procedure), frequency filtering (e.g., the masking of unwanted components in the frequency domain followed by transformation back into the spatial domain), or pixel power deviation. For details, refer to [11] to [27].

These methods can effectively remove the periodic modulations from the sparkle pattern, however the measured results can only be comparable within the data from the same filter design, because the filters are usually dependent on the pitch of the display matrix elements, i.e., optimized for the ISR at the measurement (see Table B.1).

Table B.1 – Filtering method capabilities for removing artifacts related to display matrix elements

	Moving window averaging filter (B.2.1)	**Notch filtering in frequency domain (B.2.2)**	**Pixel power deviation (Annex F)**
Remove the fundamental frequency (f_0) component of the periodic modulation of the display matrix elements from the image	This method removes the fundamental frequency and all of its harmonics.	This method removes the fundamental frequency and all of its harmonics depending on the mask design.	This method removes the fundamental frequency component.
Remove the low frequency moiré between the image of the display matrix elements and LMD pixels	With a single image, it cannot be removed. With a difference image method (see Annex E), it can be removed, but depending on moiré pattern between the image of the display matrix elements and LMD pixels.	This method removes frequencies depending on the mask design.	It can be removed, but depending on moiré pattern between the image of the display matrix elements and LMD pixels.
Filtering affects random components of measured sparkle pattern	Components within f_0 remain, but they can be removed by multiple applications of the filter.	This method removes frequencies depending on the mask design.	Data within $f_0/2$ remains.
Limitation of comparison of measured sparkle contrast	Limited within the same filter design.	Limited within the same filter design.	Limited within the same filter design.

B.2 Filtering methods

B.2.1 Filtering in spatial domain

Several filtering methods are available for separating spatial frequency components. In the case of sparkle evaluation, first of all the periodic modulations caused by the display matrix elements have to be removed. One method to completely remove all frequency components of the periodic modulation of the display matrix elements is application of the MWA process. In that case a filter kernel is used for convolution (i.e., filtering in the spatial domain) with rational/fractional dimensions in terms of LMD pixels (detector matrix elements of LMD).

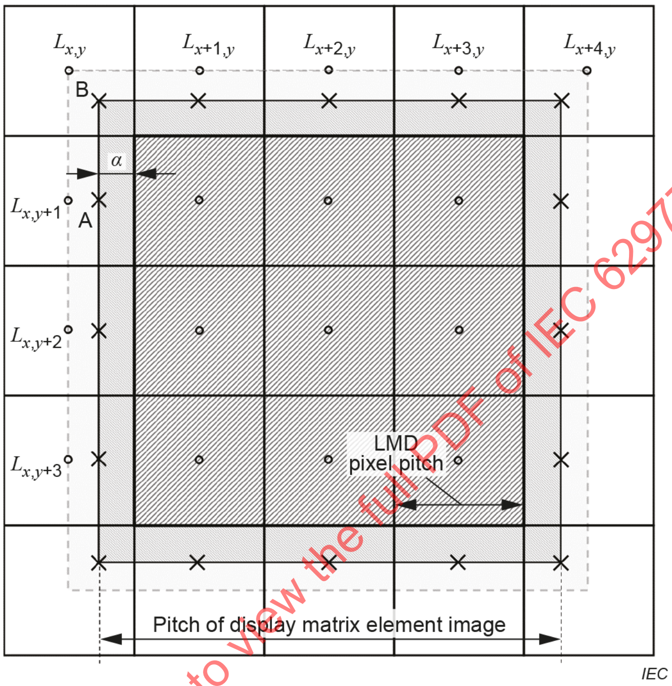


Figure B.1 – Display matrix element (grey square) in relation to the matrix of the imaging LMD detector elements (squares according to LMD pixel pitch) for the case of oversampling with an image sampling ratio of R_S = 3,5

In the recorded images the periodic modulation of the display matrix elements is removed by spatial filtering, i.e., by replacing the value of each LMD pixel (= image pixel) according to the average radiance value of the neighbouring LMD pixels. The number of adjacent elements that are usually considered in the MWA filtering process is the square of odd integers (e.g., 9, 25). Generally, without special adjustments during image acquisition, the image of one display matrix element will be sampled by a non-integer (i.e., rational/fractional) number of LMD pixels. In order to suppress periodic modulations caused by the display matrix elements, spatial filtering can be applied with a kernel that is matched to the pitch of the display matrix elements of the DUT image on the LMD detector array (specified in terms of LMD pixels). The ratio of the pitch of the LMD detector elements to the pitch of DUT matrix elements multiplied by the lens magnification (M << 1) is called an image sampling ratio (ISR) R_S. The ISR can be determined by counting a multitude of periods in a profile (see section 7.2 to section 7.5 of [21]), by discrete Fourier transformation of the profile, or by 2D discrete Fourier transformation of the image. The concept of a "rational/fractional kernel" for the ISR of 3,5 is illustrated in Figure B.1. Starting with a kernel with odd integer dimensions (core-kernel, here: 3 × 3, next odd integer < R_S), rational increments α ($0 \leq \alpha \leq 1$) are added at the periphery to form a square region that is identical to the square area on the image on the display matrix elements. The radiance values within the integer 3 × 3 kernel are weighted by 1, the vertically and horizontally surrounding values are weighted by α, and the diagonal values by α^2. If the ISR is 3,5 as illustrated in Figure B.1, then α = (3,5 – 3) / 2 = 0,25. The examples of applying an MWA filter on the sparkle pattern are shown in Figure B.2, when R_S = 4,3.

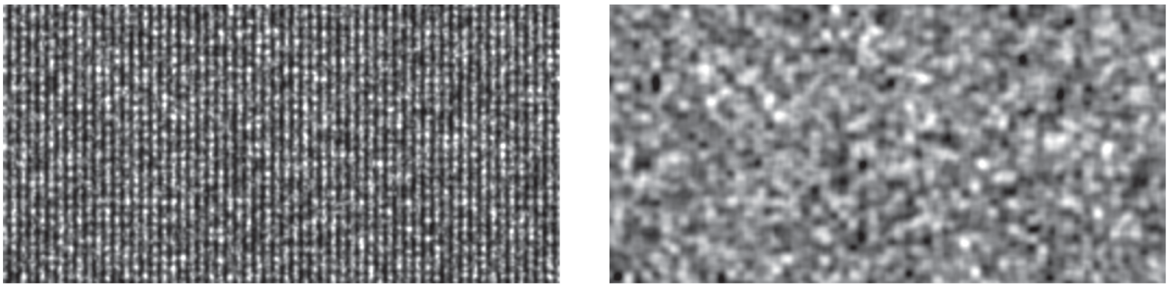


Figure B.2 – Examples of sparkle patterns at R_S = 4,3 before applying an MWA filter (left) and after applying an MWA filter (right)

The number of LMD pixels in the square kernel, k^2, is given by the square of the closest odd integer $k > R_s$, which is 25 for R_s = 3,5. The sum of the weighted radiance levels of the image is divided by the sum of the weights and then assigned to the centre LMD pixel (= image pixel). The filtered image, L^*, thus becomes:

$$L^*(x,y) = L * K = \sum_{s=-a}^{a} \sum_{t=-a}^{a} K(s,t) \times L(x+s, y+t) \qquad \text{(B.1)}$$

where

$L(x, y)$ is the radiance matrix representing the image of the DUT;

$K(s, t)$ is the square convolution kernel as illustrated in Formula (B.2);

$L^*(x, y)$ is the radiance matrix representing the filtered DUT image;

s, t are variables used during convolution;

$a = (k - 1) / 2$.

The filter kernel illustrated in Formula (B.2) can be translated across the image in steps corresponding to the LMD pixel pitch [11]. S_W is the sum of all weights used in the convolution matrix, i.e., the two-dimensional MWA filter.

NOTE When the centre of the kernel is at the periphery of the image (outermost rows and columns) non-existing picture elements can be included in the averaging. A frame-shaped edge region of width $(k - 1) / 2$ LMD pixels will thus be excluded from evaluation of the average value and the standard deviation from which the sparkle contrast is evaluated.

$$K(s,t) = \frac{1}{S_W} \begin{bmatrix} \alpha^2 & \alpha & \alpha & \alpha & \alpha^2 \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha & 1 & 1 & 1 & \alpha \\ \alpha^2 & \alpha & \alpha & \alpha & \alpha^2 \end{bmatrix} \qquad \text{(B.2)}$$

where

$S_w = (k - 2)^2 + 4\,(k - 2)\alpha + 4\alpha^2$.

Formula (B.2) shows a 5 × 5 filter kernel (k = 5) $K(s, t)$, for the case illustrated in Figure B.1, i.e., for the ISR, R_s = 3,5.

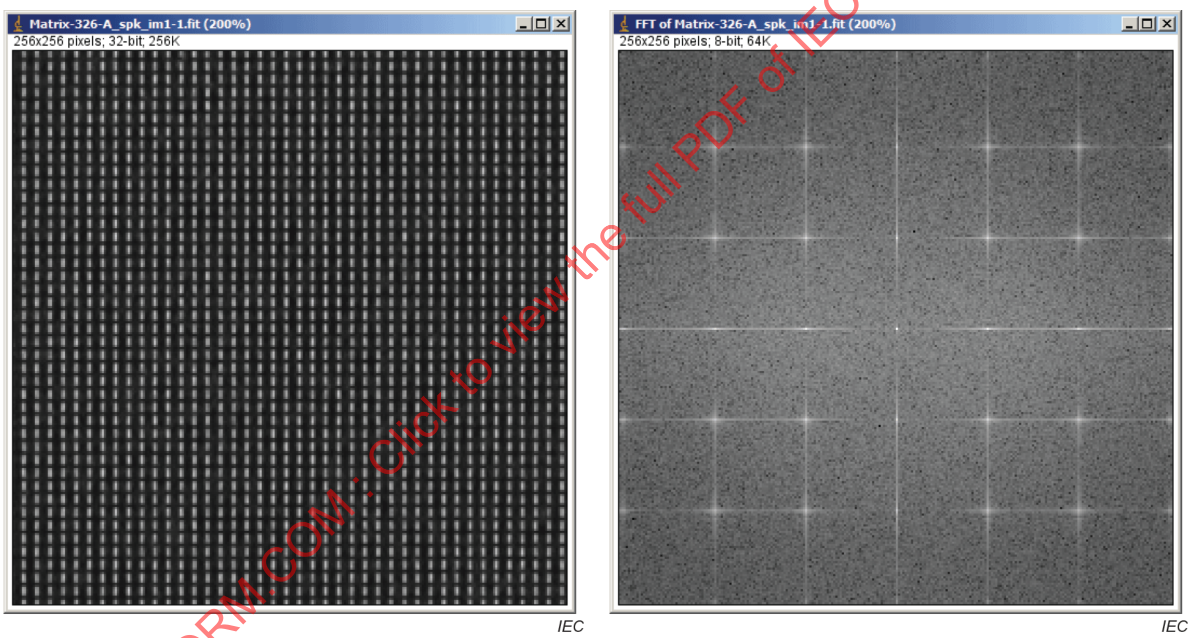
The square 2D filter kernel according to Formula (B.2) can be separated into two 1D kernels that are applied one after the other in the horizontal and the vertical direction (or vice versa). In the 1D case the convolution described here (in the case of integer dimensions) is equivalent to the “moving window averaging” operation as introduced in section B18 of [21]. The algorithm described in IDMS B18 can be extended to rational/fractional window dimensions as sketched in Formula (B.2). The average values $L^*(y)$ for row y are obtained as:

$$L^*(y) = \left[\alpha \bullet L(-a, y) + \sum_{S=a+1}^{a-1} L(x+s, y) + \alpha \bullet L(a, y) \right] \qquad \text{(B.3)}$$

This MWA filter can be easily implemented in spreadsheet software. Images, i.e. 2D arrays of radiance values, can be filtered by first filtering in one direction, for example, row after row, then followed by filtering in the other direction, i.e. column after column.

B.2.2 Filtering in frequency-domain

Two-dimensional discrete Fourier transformation reveals the frequency components that are included in the electronic image captured by the LMD, as shown in Figure B.3.



(a) Electronic image of the DUT (i.e., display matrix elements with AGL) captured at R_S = 6.

(b) Two-dimensional discrete Fourier transform of the image on the left. The box-shaped structures represent the frequencies of the display matrix elements (fundamental frequency and higher harmonic components).

NOTE A metric different from sparkle contrast can be the sum of amplitudes (magnitudes) in specific frequency ranges, excluding the components generated by the display matrix elements

Figure B.3 – Electronic images of the DUT (i.e., display matrix elements with AGL, left) and frequency components of that image used as basis for sparkle evaluation

Instead of obtaining a metric for the level of sparkle directly from summation of amplitudes (magnitudes) over specific frequency ranges, hereby excluding components generated by the display matrix elements, filtering can be achieved by the masking of unwanted components in the frequency domain followed by transformation back into the spatial domain [17], [20].

Annex C
(informative)

Hardware parameters that affect the sparkle contrast

C.1 LMD aperture setting

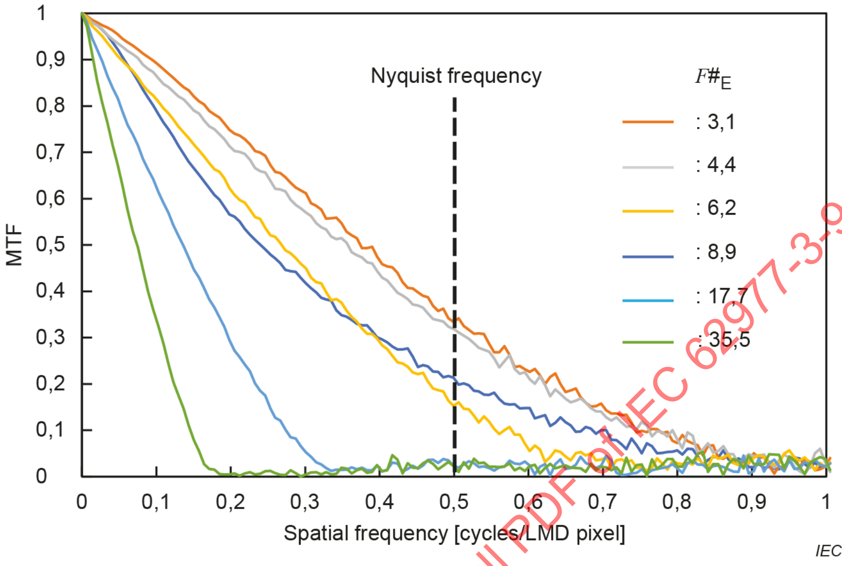


Figure C.1 – Example of the variation of the MTF of the imaging LMD under different *F*-numbers as a function of spatial frequency of LMD pixels

Figure C.1 shows an example of the variation of the modulation transfer function (MTF) of an imaging LMD with different aperture settings (effective *F*-number) at a fixed working distance as a function of the spatial frequency of LMD pixels. Even if two lenses have the same specified *F*-number and focal length, the sparkle contrast results can be different for both lenses as caused by different MTF profiles.

NOTE A higher *F*-number reduces the signal-to-noise ratio between the sparkle signal and the imaging LMD noise. This can negatively affect reproducibility of the evaluated sparkle contrast between different imaging sensors with different noise levels [22].

C.2 LMD focus

The imaging properties of the LMD strongly depend on the focusing conditions. In general, the lens focus is on the display matrix elements of the DUT, not on the AGL. Even slight deviations from the correct focusing condition can introduce unwanted and uncontrolled optical low-pass filtering. The operator can ensure accurate focusing to obtain correct results from the measurement.

C.3 Condition to avoid aliasing

Sparkle patterns consist of spatial frequency components in a wide frequency range. There is possibility of aliasing if spatial frequency components which are higher than the Nyquist frequency of LMD pixels are measured. When the cut-off frequency is set less than the Nyquist frequency of LMD pixels, the above aliasing can be avoided. The condition can be written as follows [23]:

$$\frac{1}{F\#_E \lambda} \leq \frac{1}{2P_\text{L}} = \frac{R_\text{S}}{2} \cdot \frac{m}{P_\text{D}} \tag{C.1}$$

The condition (C.1) can be also written by using $F\#$ as follows;

$$F\# \geq \frac{2}{\lambda} \cdot \frac{P_\text{L} P_\text{D}}{m R_\text{S} P_\text{L} + P_\text{D}} \tag{C.2}$$

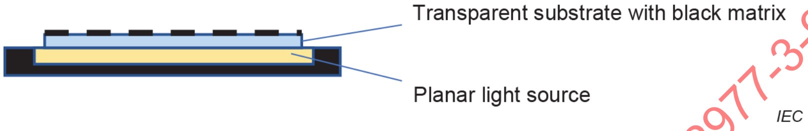
NOTE There are many parameters which affect the aliasing of the sparkle pattern such as the level of the original sparkle contrast, its frequency distribution and filtering methods as described in Clause B.2. Thus, the conditions in Formula (C.1) and Formula (C.2) do not provide a relation to their effect on the measurement accuracy of sparkle contrast.

Annex D
(informative)

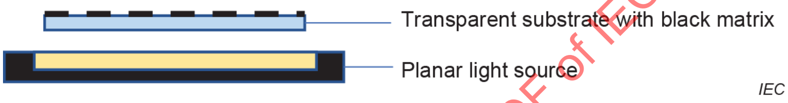
Sparkle contrast measurement with display mock-up

D.1 Display mock-up

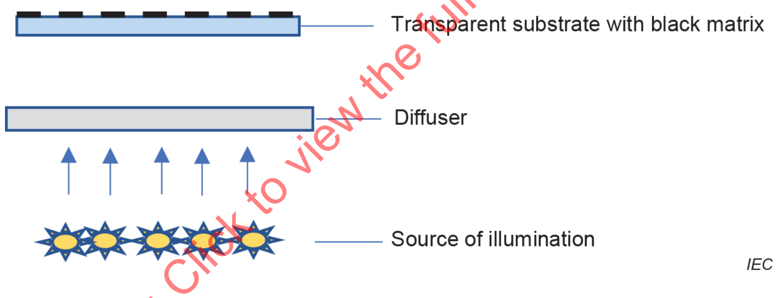
Sparkle contrast depends on the combination of the anti-glare layer and the display matrix. For the purpose of optimizing the anti-glare performance of the AGL, a display mock-up can be used instead of actual electronic displays. Generally, the display mock-up consists of 2D backlight and a plate with black matrix on the surface. Figure D.1 shows some examples of display mock-ups.



(a) Transparent substrate with black matrix on the backlight



(b) Transparent substrate with black matrix separately set in front of the backlight



(c) Transparent substrate with black matrix and diffuser illuminated by the source of illumination

NOTE Additional transparent substrate can be inserted between the AGL and the transparent substrate with black matrix, to mimic the display stack thickness. Additionally, an air gap between the AGL and the transparent substrate with black matrix can also be incorporated to reflect certain display stack configurations.

Figure D.1 – Examples of display mock-ups

D.2 Measurement

Figure D.2 shows an example of measurement configuration using a display mock-up. The AGL (film substrate or glass substrate) is put on the black matrix of the display mock-up. Through the series of measurements, only the AGL is replaced, while all other conditions are fixed.

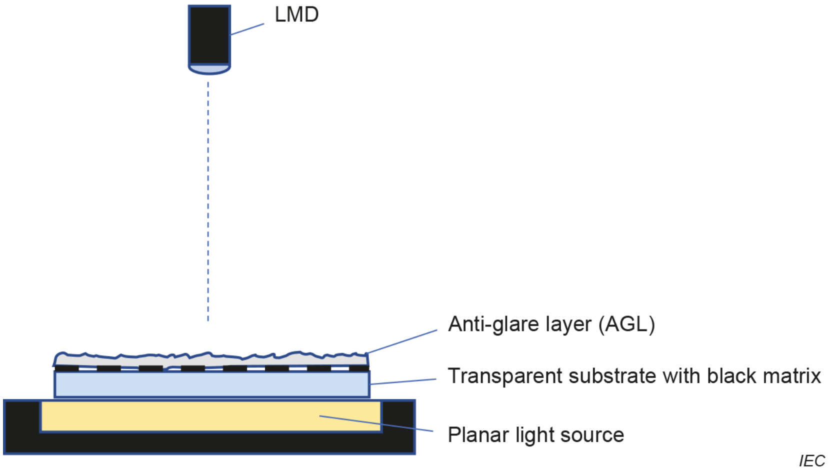


Figure D.2 – Example of measurement configuration

Annex E
(informative)

Calculation of sparkle contrast by the difference image method

E.1 Statistical background

In the field of sparkle contrast measurement, the difference image method can be used to eliminate the effect of non-periodic defects in or on the display matrix elements and gradual radiance variation [18]. Two different sparkle patterns which have same standard deviation and mean value can be obtained by displacing the AGL on the display surface. The concept of the difference image method is to subtract an image from another one to extract random components of the sparkle pattern.

Ensure that "Image1" is captured and "Image2" is captured with the AGL shifted while the display matrix and the LMD are fixed. "Image1" and "Image2" are considered to be random and statistically independent, and have the same average radiance μ. The sparkle contrast of "Image1" is σ_1 / μ, where σ_1 is the standard deviation of "Image1"; the sparkle contrast of "Image2" is σ_2 / μ, where σ_2 is the standard deviation of "Image2". If σ_1 and σ_2 have the same value σ_1, the sparkle contrast is σ/μ for both images. The "difference image" is calculated as follows: the data "Image2" is subtracted from "Image1". The "difference image" is then obtained by adding the average value m of "Image1" and "Image2" to the result of the subtraction. The standard deviation of the difference image σ_{diff} is $\sigma_{\mathrm{diff}} = \sqrt{\sigma_1{}^2 + \sigma_2{}^2} = \sqrt{2}\sigma$. Therefore, the sparkle contrast of the "difference image" is $\sigma_{\mathrm{diff}} / \mu = \sqrt{2}\sigma / \mu$, while the non-periodic defects and gradual radiance variation are cancelled by the subtraction process.

The validity of the subtraction process is supported by the randomness of the sparkle pattern. This randomness was experimentally confirmed in [7] and [20], by comparing the sparkle pattern with the incoherent speckle pattern which is already proved to be random. Moreover, the factor of $\sqrt{2}$ from the standard deviation of the subtracted image was experimentally shown in [6].

E.2 Measurement procedure of the difference image method

This method can be applied to the display when the AGL is not fixed to the display and can be shifted parallel to the display while keeping the distance between the AGL and the display matrix constant. The measurement conditions and the test pattern are given in Clause 4.

The measurement procedure is as follows:

1) Position and align the DUT and LMD according to Figure 3. Orientation of the LMD perpendicularly to the DUT surface is the preferred orientation (see 4.5.2), since all other orientations (e.g., inclination angle ≥ 2°) would introduce a variation of spatial frequencies across the recorded image and thus negatively affect the basis for further evaluation.
2) Allow sufficient time for the DUT and LMD to thermally stabilize. Sufficient warm-up time has been achieved when the radiance of the test feature to be measured varies by less than ±5 % over the entire measurement period (e.g., uniformity measurements) for a given display test pattern.
3) Correct the rotational mismatch physically between the LMD and the DUT so that the display matrix elements are parallel or perpendicular to the LMD sensor pixel matrix.
4) Focus the LMD on the display matrix elements of the DUT. Be aware that incorrect focusing can act as an optical low-pass filter and thus affect the sparkle evaluation.
5) Set the AGL on the surface of the display.
6) Capture the image as "Image1" without overflow of the detector array of the imaging LMD.

7) Shift the AGL parallel to the surface of the display.

8) Capture the image as “Image2” under the same condition as in step 6).

NOTE The shift length of the AGL is more than the auto-correlation length of the anti-glare structure (e.g., 2 mm) [18]. If this condition is fulfilled, “Image1” and “Image2” are considered to be independent, and $\sigma_{\text{diff}} / \mu = \sqrt{2}\sigma / \mu$ is expected.

E.3 Calculation of sparkle contrast by the difference image method

1) Subtract the radiance data of “Image1” from “Image2” at the corresponding addresses of each image, or vice versa, to get the subtracted image.

2) Add the average radiance value between “Image1” and “Image2” to all the addresses of the subtracted image to get the “difference image”.

3) Calculate the sparkle contrast of the “difference image” with Formula (2) in 5.4.

NOTE 1 If the average radiance values of “Image1” and “Image2” are different, the condition of the DUT (i.e., luminance level within the exposure time) will probably not be the same. In that case, the sparkle patterns of “Image1” and “Image2” can be captured again so that the average radiance values of both images will be the same.

NOTE 2 The filtering methods for removing periodic modulations from the image described in Annex B can be applied if needed.