

# INTERNATIONAL STANDARD



Laser display devices –  
Part 5-4: Optical measuring methods of colour speckle

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# INTERNATIONAL STANDARD



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**Laser display devices –  
Part 5-4: Optical measuring methods of colour speckle**

INTERNATIONAL  
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## Part 5-4: Optical measuring methods of colour speckle

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FDIS	Report on voting
110/926/FDIS	110/938/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

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## LASER DISPLAY DEVICES –

### Part 5-4: Optical measuring methods of colour speckle

#### 1 Scope

This part of IEC 62906 specifies the fundamental colour speckle distribution in CIE colour systems and the measuring methods of the colour speckle of laser display devices (LDDs).

#### 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62906-1-2, *Laser display devices – Part 1-2: Vocabulary and letter symbols*

IEC 62906-5-2:2016, *Laser display devices – Part 5-2: Optical measuring methods of speckle contrast*

CIE publication 15:2004, *Colorimetry*

#### 3 Terms, definitions, letter symbols and abbreviated terms

For the purposes of this document, the following terms and definitions given in IEC 62906-1-2 and the following apply.

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

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

##### 3.1 Fundamental terms

###### 3.1.1

###### **colour speckle distribution**

colour distribution in a specified colour space of the speckle patterns which are generated by colour mixing of monochromatic screen speckles

###### 3.1.2

###### **photometric speckle distribution**

distribution of photometric variables such as illuminance, luminance or luminous flux of a colour speckle pattern which are generated by colour mixing of monochromatic screen speckles

##### 3.2 Terms related to colour speckle distribution

###### 3.2.1

###### **colour speckle variance**

variance for either of the chromaticity coordinates of colour speckle distribution data, used as one of the metrics of colour speckle distribution

### 3.2.2

#### **colour speckle covariance**

covariance between chromaticity coordinates of colour speckle distribution data, used as one of the metrics of colour speckle distribution

### 3.2.3

#### **photometric speckle contrast**

#### **photometric speckle contrast ratio**

ratio of the standard deviation to the average of the photometric distribution, such as illuminance, luminance, or luminous flux

### 3.2.4

#### **colour difference variance**

variance of distribution of colour difference of colour speckle between the target chromaticity in an appropriate colour space

Note 1 to entry: See Annex B.

## 3.3 Terms related to spatial variation

### 3.3.1

#### **angular colour speckle variation**

variation of colour speckle contrast and variance/covariance with zenith ( $\theta$ ) or azimuth ( $\varphi$ ) angles on a point of the projection plane (screen)

### 3.3.2

#### **photometric speckle contrast uniformity/non-uniformity**

uniformity or non-uniformity of photometric speckle contrast on the predefined points of the projection plane (screen)

### 3.3.3

#### **colour speckle variance/covariance non-uniformity**

non-uniformity of colour speckle variance/covariance on the predefined points of the projection plane (screen)

## 3.4 Letter symbols

$\bar{x}(\lambda), \lambda, \lambda, \bar{y}(\lambda), \bar{z}(\lambda)$	Colour matching functions
$X, Y, Z$	Tristimulus values
$S_{B,G,R}(\lambda)$	Spectral power distribution for each B, G, R (normalized as unity)
$r_B, r_G, r_R$	Average power ratio for each B, G, R ( $r_B + r_G + r_R = 1$ )
$E$	Monochromatic speckle (relative illuminance) distributions
$E_{B,G,R}$	Monochromatic speckle distributions for each B, G, R
$M$	Number of independent coherent light sources
$C_s$	Monochromatic speckle contrast
$C_{s-B,G,R}$	Monochromatic speckle contrast for each B, G, R
$C_{ps}$	Photometric speckle contrast
$\sigma$	Standard deviation of monochromatic spatial speckle distribution
$\sigma_u^2, \sigma_v^2$	Colour speckle variance (CIE 1976)
$\mu_{u'v'}$	Colour speckle covariance (CIE 1976)
$NU_{ps}$	Photometric speckle contrast non-uniformity

$NU_{\text{csu}'}$ , $NU_{\text{csv}'}$	Colour speckle variance non-uniformity
$NU_{\text{csu}'v'}$	Colour speckle covariance non-uniformity

### 3.5 Abbreviated terms

B,G,R (BGR)	Blue, green, red
DUT	Device under test
FDS	Fully developed speckle
FWHM	Full width at half maximum
LD	Laser diode
LDD	Laser display device
LMD	Light measuring device
MTF	Modulation transfer function

## 4 Theory of colour speckle

### 4.1 General

The colour speckle of laser display devices (LDDs) is defined as speckle when the light source is multi-coloured (see IEC 62906-1-2). It is recognized as fine colour patterns different from the colour intended to be displayed (see Annex A).

The colour speckle of the LDDs using coherent or partially coherent light sources emitting at different wavelengths is created by spatially superposing their monochromatic speckle patterns. Particularly for hybrid LDDs, the colour speckle is also created by superposing such monochromatic speckle patterns on speckle-less colour patterns generated by incoherent light sources.

The colour speckle is theoretically obtained as distribution in CIE colour spaces (see CIE publication 15:2004) using the measured data of monochromatic speckles created by coherent or partially coherent light sources.

Clause 4 specifies the colour speckle creation mechanism, examples of colour speckle distribution in CIE 1976 chromaticity diagram and the evaluation indices.

### 4.2 Mechanism for generating colour speckle

Subclause 4.2 specifies the mechanism for generating colour speckle.

Monochromatic speckle contrast  $C_s$  is expressed as follows:

$$C_s = \frac{\sigma}{\langle E \rangle_T} \quad (1)$$

where,  $E$  is the relative irradiance of spatial distribution for monochromatic speckle,  $\langle E \rangle_T$  is the total average in the probability density function shown later, and  $\sigma$  is the standard deviation. Speckle is recognized as an interference pattern projected on human retina. Therefore, illuminance  $E$  on the retina is used here. This is the same definition as in IEC 62906-5-2.

The number of independent coherent light sources is defined as  $M$ . Therefore, the probability density function of speckle is given by the gamma distribution as follows [1], [3]<sup>1</sup>:

$$p_M(E) = \frac{M^M E^{M-1}}{\Gamma(M) \langle E \rangle_T^M} \exp\left\{-\frac{ME}{\langle E \rangle_T}\right\} \quad (2)$$

where,  $\Gamma(M)$  is the gamma function. The number  $M$  is usually an integer. However,  $M$  can be used as a decimal number.

Formula (2) is normalized as  $\langle E \rangle_T / M = 1$  for the colour speckle estimation. The monochromatic speckle contrast given by Formula (1) is then expressed as follows:

$$C_s = \frac{\sqrt{M}}{\langle E \rangle_T} = \frac{1}{\sqrt{M}} \quad (3)$$

Using Formula (3), the probability density function in Formula (2) is simply rewritten as a function of  $C_s$  instead of  $M$ .

$$p(E) = \frac{E^{C_s^{-2}-1}}{\Gamma(C_s^{-2})} \exp(-E) \quad (4)$$

The illuminance values  $E$  at a given  $C_s$  value can be obtained statistically by generating random numbers for the inverse function of Formula (4). However, it should be noted that  $E$  shall be scaled down as  $E/M$  because it has already been normalized as  $\langle E \rangle_T / M = 1$ . This statistical speckle formulation is based on radiometry.

To apply the above radiometric formulation to colour speckle, it is necessary to couple it with colourimetry. For BGR laser light sources, the normalized spectral power distribution is expressed as  $S_{B,G,R}(\lambda)$  ( $\int S_{B,G,R}(\lambda) d\lambda = 1$ ). To realize the target white point by mixing the BGR colours, the average power ratio,  $r_B, r_G, r_R$ , ( $r_B + r_G + r_R = 1$ ) shall be determined. The target white point is not affected by monochromatic speckles. In actual measurements, it is obtained by averaging the spatial distribution of each monochromatic speckle. The monochromatic speckle distributions for each colour are expressed as  $E_{B,G,R}$ . In case of incoherence,  $E_{B,G,R} = 1$ .

Therefore, the tristimulus values,  $X, Y$ , and  $Z$  are given by

$$\begin{aligned} X &= \int_{380}^{780} \bar{x}(\lambda) \cdot \{r_B E_B S_B(\lambda) + r_G E_G S_G(\lambda) + r_R E_R S_R(\lambda)\} d\lambda \\ Y &= \int_{380}^{780} \bar{y}(\lambda) \cdot \{r_B E_B S_B(\lambda) + r_G E_G S_G(\lambda) + r_R E_R S_R(\lambda)\} d\lambda \\ Z &= \int_{380}^{780} \bar{z}(\lambda) \cdot \{r_B E_B S_B(\lambda) + r_G E_G S_G(\lambda) + r_R E_R S_R(\lambda)\} d\lambda \end{aligned} \quad (5)$$

where,  $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$  are the colour matching functions.

<sup>1</sup> Numbers in square brackets refer to the Bibliography.

The CIE 1931 chromaticity coordinates,  $x$ ,  $y$ , are given by

$$x = \frac{X}{X+Y+Z}, \quad y = \frac{Y}{X+Y+Z} \quad (6)$$

The CIE 1976 chromaticity coordinates,  $u'$ ,  $v'$  are thus given by

$$u' = \frac{4x}{-2x+12y+3} = \frac{4X}{X+15Y+3Z}, \quad v' = \frac{9y}{-2x+12y+3} = \frac{9Y}{X+15Y+3Z} \quad (7)$$

The above formulation can be applied in this document not only to the case of a narrow spectral linewidth of BGR LDs but also to the much wider spectra of an incoherent light source such as phosphor emission.

In the theoretical analysis of the colour speckle distribution,  $S_{B,G,R}(\lambda)$  shall be given first. Then the target chromaticity point is determined. Next, the power ratio  $r_B$ ,  $r_G$ ,  $r_R$  shall be calculated to realize the target chromaticity. After that, the monochromatic speckles,  $r_B E_B S_B(\lambda)$ ,  $r_G E_G S_G(\lambda)$ ,  $r_R E_R S_R(\lambda)$  are calculated by generating a random number using Formula (4) at the given  $C_s$  values for each B, G, R colour, which are denoted as  $C_{s-B}$ ,  $C_{s-G}$ ,  $C_{s-R}$ .

Repeating the above procedure, the colour speckle distribution  $x$ ,  $y$  can be obtained in the CIE 1931 chromaticity diagram using Formula (6), or  $u'$ ,  $v'$  in the CIE 1976 chromaticity diagram using Formula (7).

If  $Y$  only is used, the distribution of the relative illuminance, luminance or luminous flux, as photometric speckle distribution, can be obtained.

## 5 Calculation methods of colour speckle

### 5.1 General

For the calculation of colour speckle, it is necessary to determine the following physical parameters on the imaging plane:

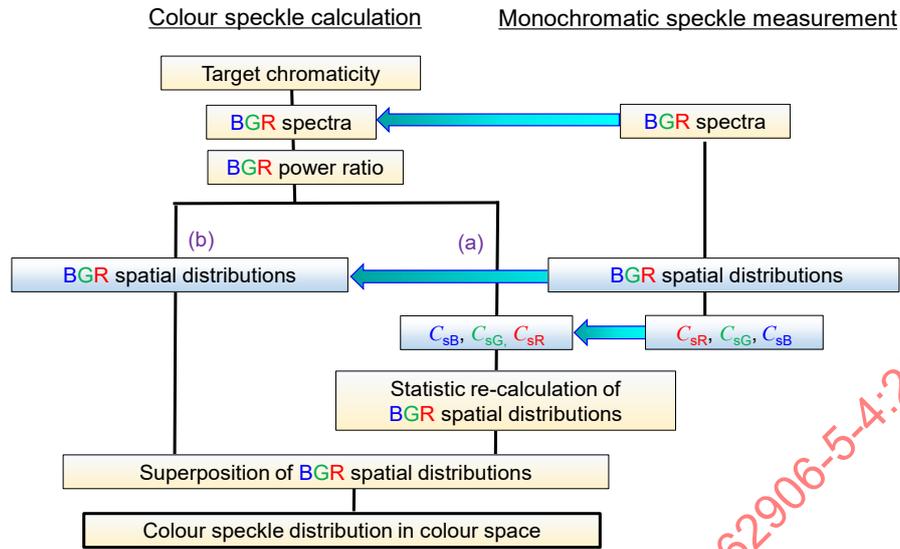
- target chromaticity (determine),
- spectra of light sources (assumed or measure),
- spectral power ratio of the BGR outputs (calculated to realize the target chromaticity),
- speckle contrast of the BGR outputs (assume or measure).

The flow charts of the calculation methods of colour speckle are illustrated in Figure 1.

Two calculation methods of colour speckle are given as follows.

- Method superposing statistically-calculated spatial distribution of BGR monochromatic speckles using BGR speckle contrast values,  $C_{s-B}$ ,  $C_{s-G}$ ,  $C_{s-R}$ .
- Method superposing the measured spatial distribution of BGR monochromatic speckles.

The above two methods theoretically reach the same results within the statistical errors based on the law of large numbers.



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Figure 1 – Two speckle measuring methods and their flow charts

### 5.2 Measuring method of spectral behaviour of BGR light sources

The normalized spectral power distribution  $S_{B,G,R}(\lambda)$  ( $\int S_{B,G,R}(\lambda)d\lambda = 1$ ) shall be obtained to calculate colour speckle distribution because it is necessary for calculating tristimulus values,  $X$ ,  $Y$ , and  $Z$ , as in 4.2.

The spectral measurements should be carried out at the driving currents of the BGR LDs for the light output powers of each BGR LD realizing the target chromaticity of the measurement. This is because  $S_{B,G,R}(\lambda)$  usually varies with the driving currents or modulation method of the LDs.

The spectral measurement of coherent light sources such as RGB LDs (laser diodes) of which linewidth is much narrower than LEDs requires an LMD with higher resolution of wavelength, such as a spectrometer or a spectrum analyser (see IEC 62906-5-2:2016, 4.5.3; examples of LD spectra are shown in IEC 62906-5-2:2016, Annex A). The accuracy of  $S_{B,G,R}(\lambda)$  measurement affects the calculation accuracy of colour gamut and/or chromaticity coordinates.

The spectral measurement of incoherent light sources with a broad spectrum can be carried out by the conventional methods.

If the LDD (DUT) uses BGR colour filters,  $S_{B,G,R}(\lambda)$  shall be measured or calculated through the colour filters.

### 5.3 Target chromaticity

The target chromaticity shall be determined for the colour speckle measurement. The target chromaticity can be chosen at any point within the colour gamut created by the BGR spectral power distribution  $S_{B,G,R}(\lambda)$ . It should be chosen at a white point because it is easier to observe an effect of each of the BGR colours on colour speckle distribution.

It should be noted that the target chromaticity is theoretically equal to the average chromaticity of the colour speckle distribution.

Figure 2 illustrates an example of the chromaticity diagram plotting the colour gamut triangle for BT.2020 (Recommendation ITU-R BT.2020-2 [6]). The target chromaticity,  $u' = 0,198$ ,  $v' = 0,468$  corresponds to the BT.2020 reference white point. The BGR points are plotted slightly inside the wavelength rim because  $S_{B,G,R}(\lambda)$  is assumed to have a Lorentzian spectral profile with an FWHM of 2 nm as in Figure 3. This profile is approximately equal to actual high-power BGR LDs. It should be noted that the peak wavelengths are 449 nm, 520 nm, and 636 nm, which are not perfectly in accordance with BT.2020 parameter values. They are chosen for comparison with the measured results shown in 5.7, considering availability of LDs.

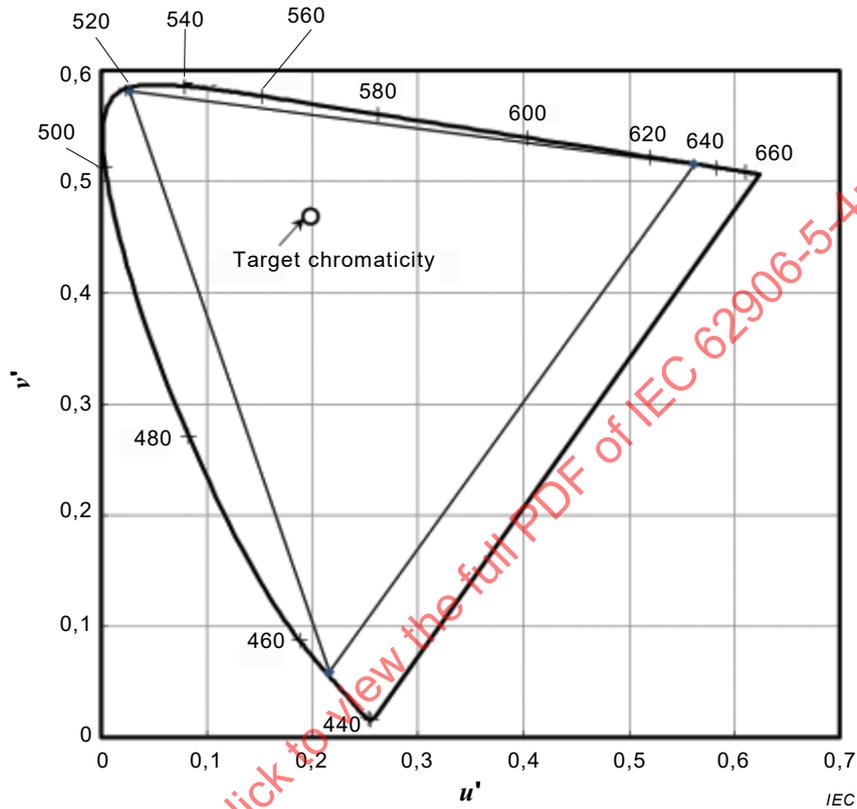


Figure 2 – Target chromaticity and colour gamut

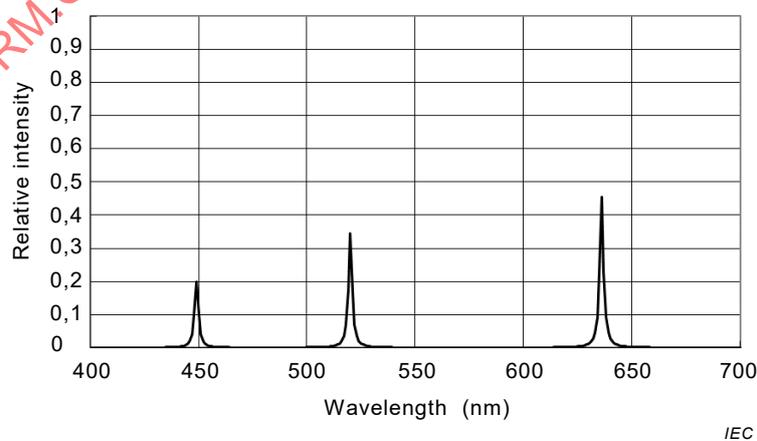


Figure 3 –  $S_{B,G,R}(\lambda)$  with an FWHM of 2 nm

#### 5.4 Adjustment of BGR power ratio

The BGR power ratio on the projection screen,  $r_B, r_G, r_R$ , for the realization of the target chromaticity shall be determined as shown in 4.2. This is the method common to the conventional projector using incoherent BGR light sources. In actual measurements, the target chromaticity is adjusted by changing the BGR power ratio. For colour speckle measurements, it is approximately equal to the average chromaticity of colour speckle when the speckle data are statistically large enough.

An example of the methods for calculating  $r_B, r_G, r_R$  is shown below using Figure 4. This method has two steps, and considers the line segments from one primary colour point to the cross-point with the line connecting the other two primary colour points, including the target point. In Figure 4, the primary colour is green and denoted as the point G, the cross-point with the BR-segment is denoted as P, and the target point is W. The line segment from G to P on the BR segment is called the G-BR line.

- Step 1: Calculation of BR power ratio,  $r'_B, r'_R$  ( $r'_B + r'_R = 1$ )

The BR power ratio,  $r'_B, r'_R$  is calculated on the BR line first. The point P is the tentative target chromaticity for obtaining  $r'_B, r'_R$ . It is obtained by changing either  $r'_B$  or  $r'_R$  linearly on the BR line.

- Step 2: Calculation of GP power ratio,  $r_G, r_P$  ( $r_G + r_P = 1$ )

The GP power ratio,  $r_G, r_P$  is then calculated on the GP line. This time, the point W is the target chromaticity for obtaining  $r_G, r_P$  on the GP line. It is obtained similarly by changing either  $r_G$  or  $r_P$  linearly on the GP line. Using the result of step 1, the final BR power ratios  $r_B$  and  $r_R$  are obtained as,  $r_B = r_P r'_B$  and  $r_R = r_P r'_R$ , respectively ( $r_B, r_G, r_R = r_P r'_B, r_G, r_P r'_R, r_B + r_G + r_R = 1$ ).

The above method is applicable to the other line segment arrangements, such as the R-GB line, or the B-GR line.

As in Figure 4 the BGR power ratio for realizing the target chromaticity (the BT.2020 reference white) is calculated as  $r_B, r_G, r_R = 0,200: 0,345: 0,456$  (see also Figure 3).

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The measuring method of the BGR monochromatic speckle contrasts  $C_{s-B}$ ,  $C_{s-G}$ ,  $C_{s-R}$  is well-established as in IEC 62906-5-2. The measurements of the BGR speckle contrasts  $C_{s-B}$ ,  $C_{s-G}$ ,  $C_{s-R}$  shall be compliant with IEC 62906-5-2.

### 5.5.2 Examples of measured distributions

Examples of colour speckle distributions and photometric speckle distributions with the same speckle contrast values for all colours are given.

Figure 5 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram, plotting the chromaticity of each of 10 000 spatial data for the case where  $C_{s-B} = 100\%$ ,  $C_{s-G} = 100\%$ ,  $C_{s-R} = 100\%$ , which is fully developed speckle (FDS). As Kuroda et.al demonstrated in [1], the colour speckle distribution spreads all over the gamut triangle formed by the apex points of the BGR wavelengths. The photometric speckle distribution, such as illuminance, luminance or flux, is shown in the histogram of Figure 6. The histogram spreads widely from less than a tenth of the average to more than three times the average.

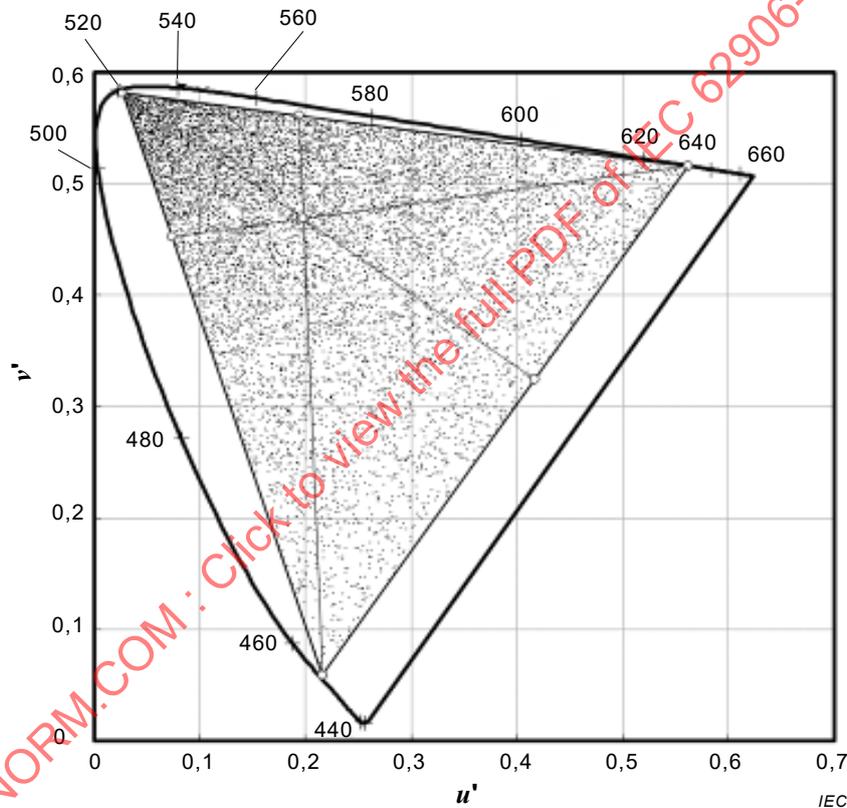
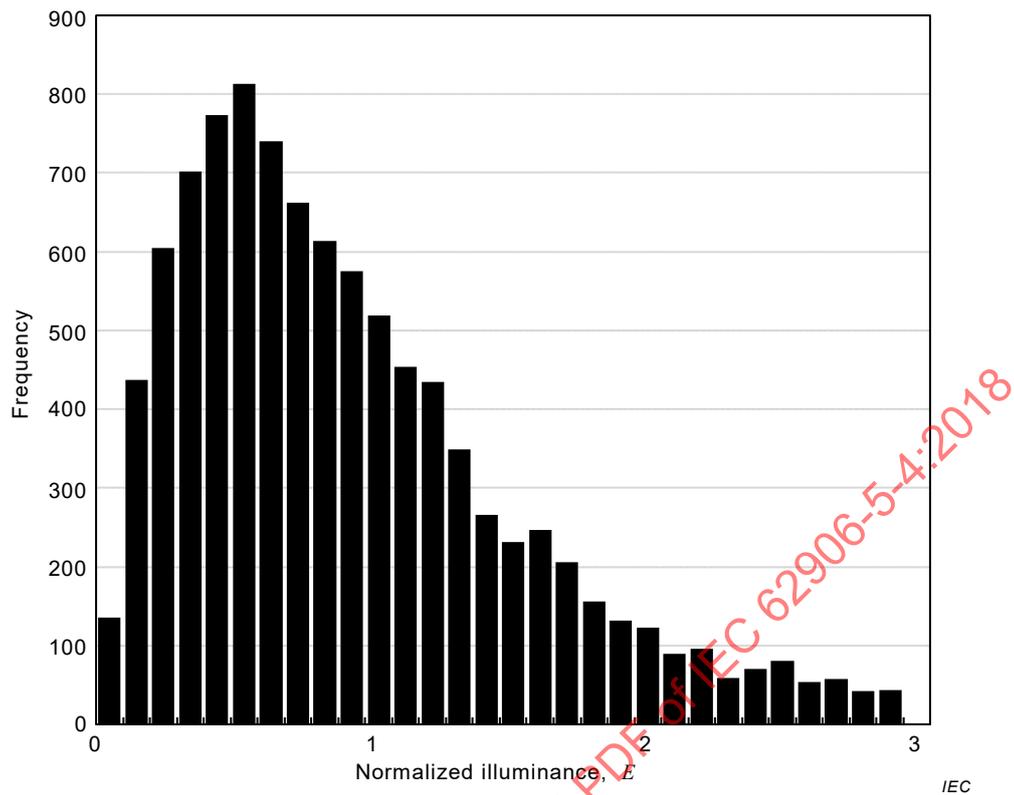


Figure 5 – Colour speckle distribution for  $C_{s-B} = 100\%$ ,  $C_{s-G} = 100\%$ ,  $C_{s-R} = 100\%$



**Figure 6 – Photometric speckle distribution for  $C_{s-B} = 100\%$ ,  $C_{s-G} = 100\%$ ,  $C_{s-R} = 100\%$**

Figure 7 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 50\%$ ,  $C_{s-G} = 50\%$ ,  $C_{s-R} = 50\%$ . The colour speckle distribution becomes much smaller than the gamut triangle. The photometric speckle distribution is shown in the histogram of Figure 8. The histogram distributes more narrowly.

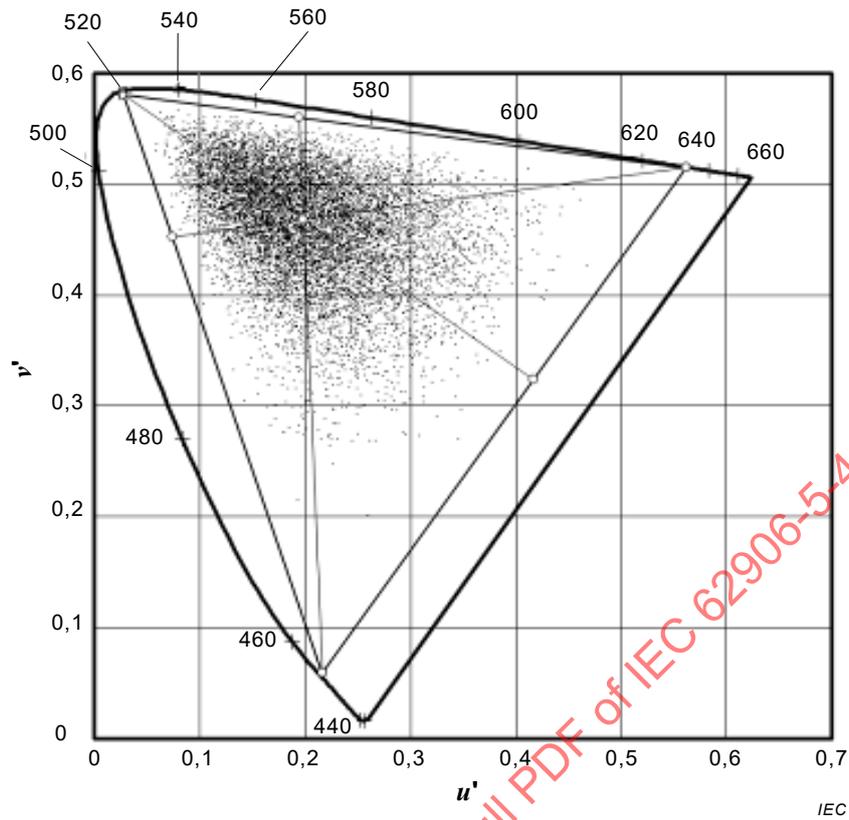


Figure 7 – Colour speckle distribution for  $C_{s-B} = 50 \%$ ,  $C_{s-G} = 50 \%$ ,  $C_{s-R} = 50 \%$

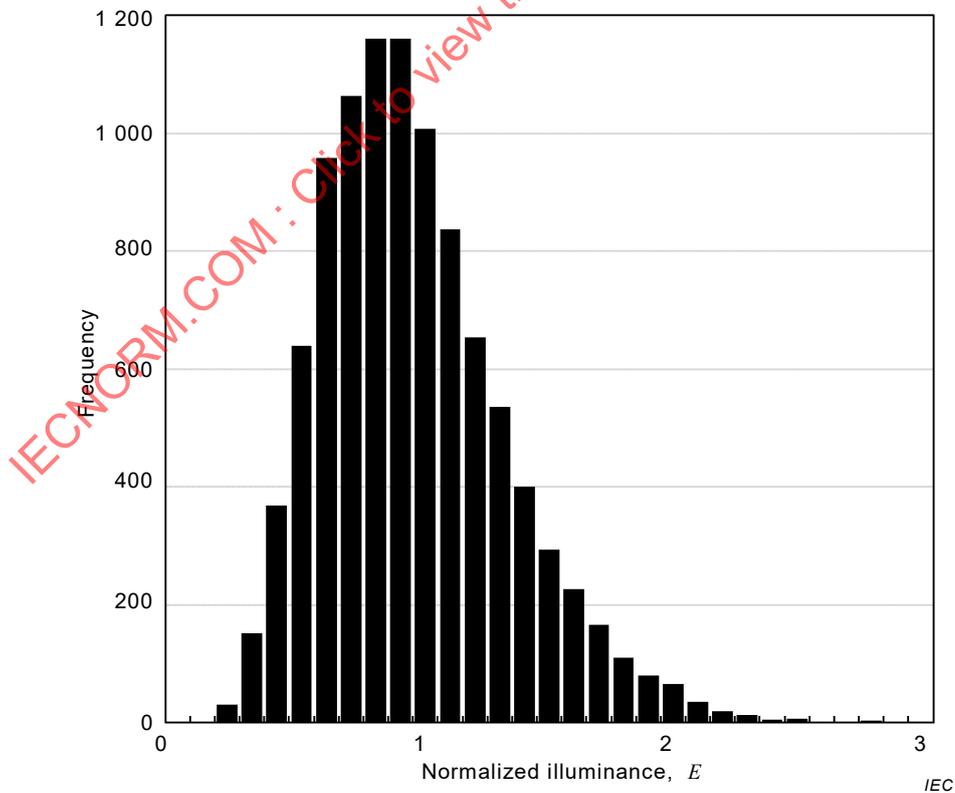


Figure 8 – Photometric speckle distribution for  $C_{s-B} = 50 \%$ ,  $C_{s-G} = 50 \%$ ,  $C_{s-R} = 50 \%$

Figure 9 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 10 \%$ ,  $C_{s-G} = 10 \%$ ,  $C_{s-R} = 10 \%$ . The colour speckle distribution is

converging on the target white chromaticity. The photometric speckle distribution is shown in the histogram of Figure 10. The photometric speckle distribution also converges on the average within almost 0,8 to 1,2.

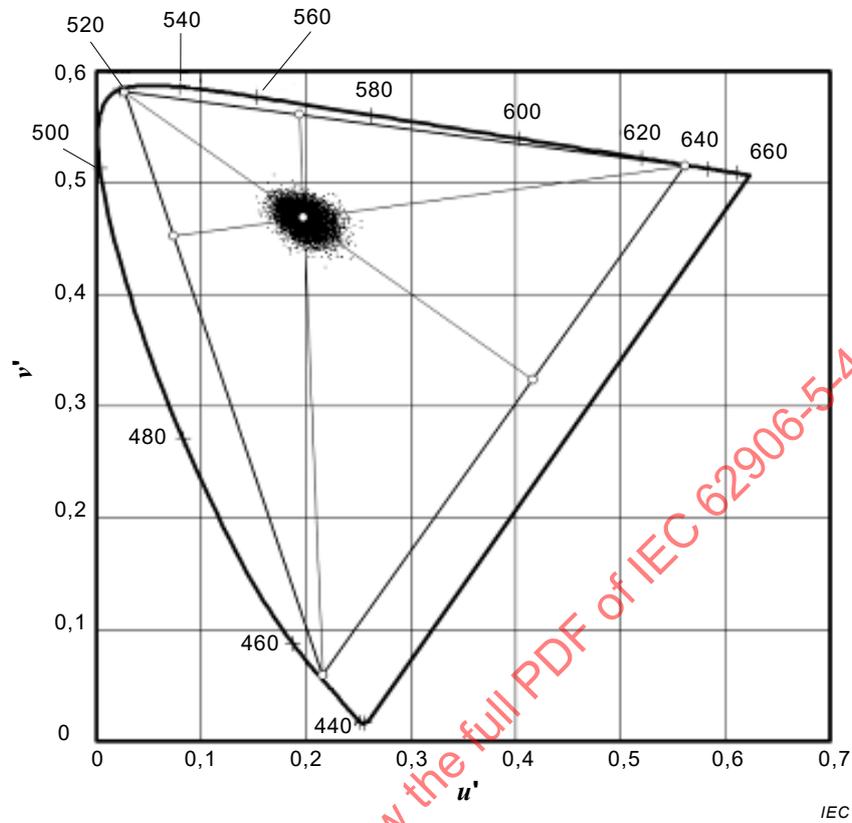
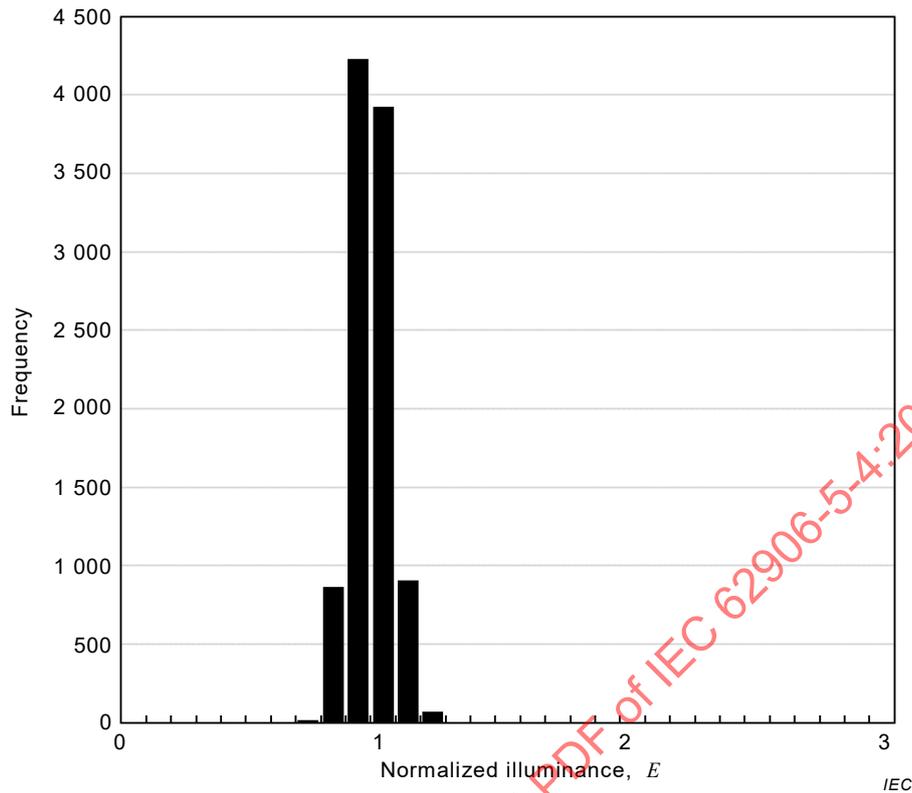


Figure 9 – Colour speckle distribution for  $C_{s-B} = 10\%$ ,  $C_{s-G} = 10\%$ ,  $C_{s-R} = 10\%$



**Figure 10 – Photometric speckle distribution for  $C_{s-B} = 10\%$ ,  $C_{s-G} = 10\%$ ,  $C_{s-R} = 10\%$**

The other specific examples of colour speckle distributions and photometric speckle distributions are shown in Annex B. The cases when the speckle contrast of one of the primary colours is 90 % and the others are 1 % are shown in Clause B.1, and the cases when the speckle contrast of two of the primary colours is 90 % and the other is 1 % are shown in Clause B.2.

### 5.6 Evaluation metrics

The evaluation metrics for colour speckle are specified in 5.6.

The photometric speckle contrast ratio  $C_{ps}$  is defined in 3.2.3 as the standard deviation  $\sigma_Y$  to the average of the photometric distribution  $\langle Y \rangle$ , such as illuminance, luminance, or luminous flux. This is mathematically analogous to the monochromatic speckle contrast. However, because of additive-mixing of BGR colours which have different luminous sensitivity values,  $C_{ps}$  is not equal to unity even for the case of fully-developed speckle ( $C_{s-B} = 100\%$ ,  $C_{s-G} = 100\%$ ,  $C_{s-R} = 100\%$ ). In fact, from the distribution in Figure 6,  $C_{ps}$  is calculated to be 75,2 %.

$$C_{ps} = \frac{\sigma_Y}{\langle Y \rangle} \tag{8}$$

Colour speckle variance is defined as the variance of colour speckle chromaticity distribution, and covariance is defined as the covariance of colour speckle chromaticity distribution in 3.2.1 and 3.2.2, respectively. The variance  $\sigma_{u'}^2$ ,  $\sigma_{v'}^2$  and covariance  $\mu_{u'v'}$  in the CIE 1976 colour system are mathematically defined as follows.

$$\sigma_{u'}^2 = \langle (u' - \langle u' \rangle)^2 \rangle$$

$$\sigma_v^2 = \langle (v' - \langle v' \rangle)^2 \rangle$$

$$\mu_{u'v'} = \langle (u' - \langle u' \rangle)(v' - \langle v' \rangle) \rangle \quad (9)$$

The values of the above metrics calculated for the examples in Figure 5 to Figure 10 are shown in Table 1. The examples in Annex B are also shown in Table 1. Colour speckle distributions and photometric speckle distributions show a variety of patterns depending on the combination of BGR parameters. It is important for the understanding of colour speckle behaviours to evaluate both the distribution patterns and the metrics. Therefore, the colour speckle distribution, the photometric speckle distribution and their metrics given in this document are fundamental tools for understanding colour speckle.

As in the examples in Clause B.1, the colour speckle distribution aligns around the B-GR line, the G-BR line or the R-BG line. For such cases, the variance/covariance in a parallel or perpendicular direction to the B-GR line, the G-BR line or the R-BG line should be added if necessary. The variance/covariance involving these lines is shown in Table 1 to Table 3.

**Table 1 – Values of measurement metrics for the calculated examples**

$C_{s-B}$	$C_{s-G}$	$C_{s-R}$	Figure	$u', v'$ variance/covariance			B-GR line		G-BR line		R-BG line		$C_{ps}$
				$\sigma_{u'}^2$	$\sigma_{v'}^2$	$\mu_{u'v'}$	//	⊥	//	⊥	//	⊥	
(%)	(%)	(%)		(10 <sup>-5</sup> )									(%)
100	100	100	5, 6	1 365	949	-274	974	1 340	1 491	823	1 289	1 025	75
50	50	50	7, 8	422	243	-115	254	412	474	192	390	276	37
10	10	10	9, 10	18	10	-5	10	17	20	7	16	11	8
90	1	1	B.1, B.2	1	330	-15	331	0	115	217	3	329	2
1	90	1	B.3, B.4	682	298	-450	339	641	979	0	561	418	63
1	1	90	B.5, B.6	480	8	62	4	485	280	208	488	8	25
90	1	90	B.7, B.8	530	363	-1	364	530	480	414	527	366	26
1	90	90	B.9, B.10	1 051	521	-301	549	1 015	1 167	405	966	606	67
90	90	1	B.11, B.12	783	651	-340	682	753	1 056	379	695	695	62

## 5.7 Calculation method (b) using the measured spatial distribution of BGR monochromatic speckles

### 5.7.1 General

The colour speckle distribution can also be calculated using the monochromatic speckle distributions for each colour  $E_{B,G,R}$  as in Formulae (5) to (7) after determination of the normalized spectral power distribution  $S_{B,G,R}(\lambda)$  and the BGR power ratio  $r_{B,G,R}$ .

The calculation method (b) uses the two-dimensional spatial distribution data of BGR monochromatic speckles before obtaining speckle contrasts  $C_{s-B}$ ,  $C_{s-G}$ ,  $C_{s-R}$ . Therefore, many more background effects under actual experiment conditions can be reflected on the results than method (a) specified in 5.5.

### 5.7.2 Examples of measured distributions

Examples of method (b) are shown in 5.7.2.

The size of the pixel data measured by the method of monochromatic speckle contrast is  $190 \times 196 = 37\,240$ . The consecutive  $100 \times 100 = 10\,000$  data in the upper left region are picked up to obtain colour speckle distribution. The original data are processed to eliminate the background effects specified in [2].

Figure 11 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 9,2 \%$ ,  $C_{s-G} = 9,7 \%$ ,  $C_{s-R} = 9,2 \%$ . Figure 12 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 9,2 \%$ ,  $C_{s-G} = 19,2 \%$ ,  $C_{s-R} = 23,2 \%$ . The speckle contrasts for each BGR monochromatic speckle,  $C_{s-B}$ ,  $C_{s-G}$ ,  $C_{s-R}$  are calculated using the data in the upper left regions of the measured and processed data.

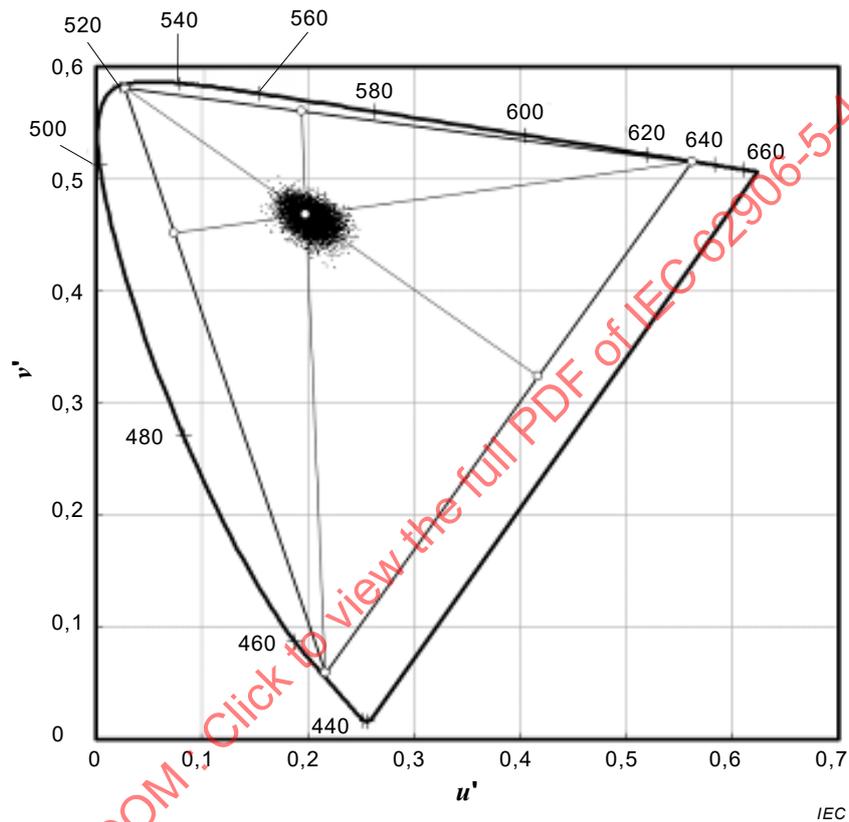


Figure 11 – Colour speckle distribution for  $C_{s-B} = 9,2 \%$ ,  $C_{s-G} = 9,7 \%$ ,  $C_{s-R} = 9,2 \%$  obtained by method (b)

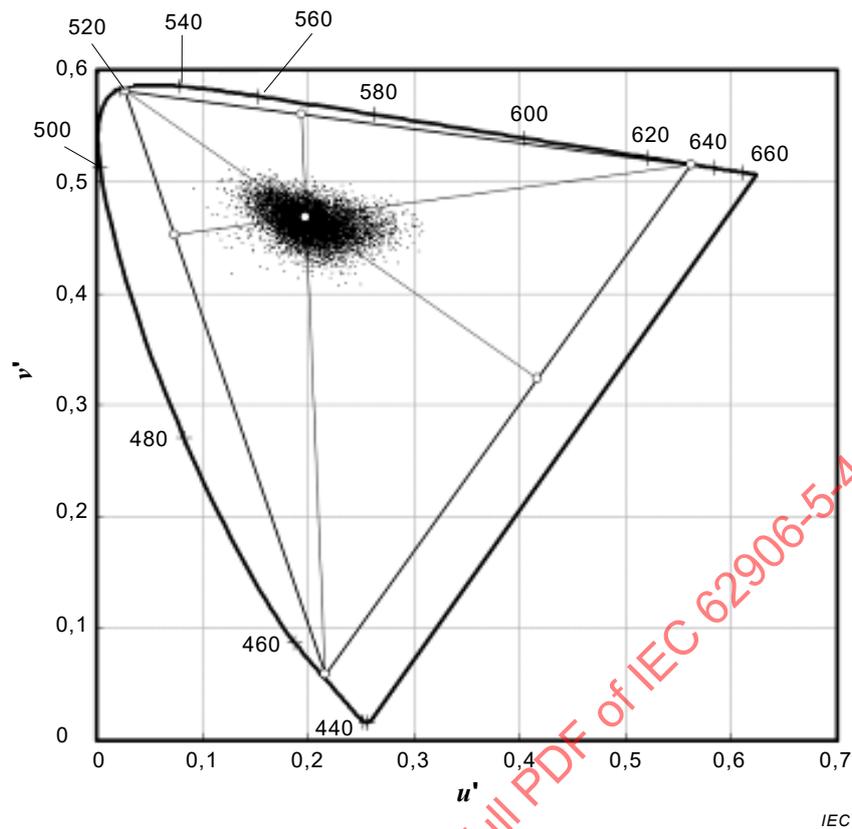


Figure 12 – Colour speckle distribution for  $C_{s-B} = 9,2\%$ ,  $C_{s-G} = 19,2\%$ ,  $C_{s-R} = 23,2\%$  obtained by method (b)

### 5.7.3 Comparison between methods (a) and (b)

The examples shown in the 5.7.2 are compared with the results of the calculation method (a).

Figure 13 illustrates a colour speckle distribution for  $C_{s-B} = 9,2\%$ ,  $C_{s-G} = 9,7\%$ ,  $C_{s-R} = 9,2\%$ , using calculation method (a). Figure 14 illustrates a colour speckle distribution for  $C_{s-B} = 9,2\%$ ,  $C_{s-G} = 19,2\%$ ,  $C_{s-R} = 23,2\%$ , using calculation method (a).

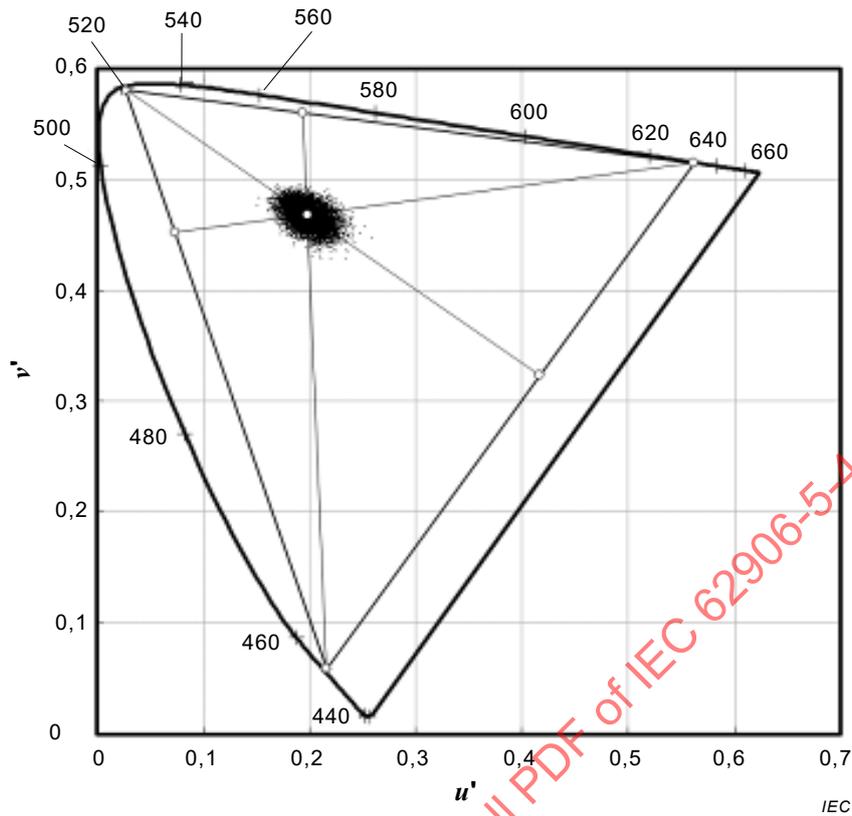


Figure 13 – Colour speckle distribution for  $C_{S-B} = 9,2 \%$ ,  $C_{S-G} = 9,7 \%$ ,  $C_{S-R} = 9,2 \%$  obtained by method (a)

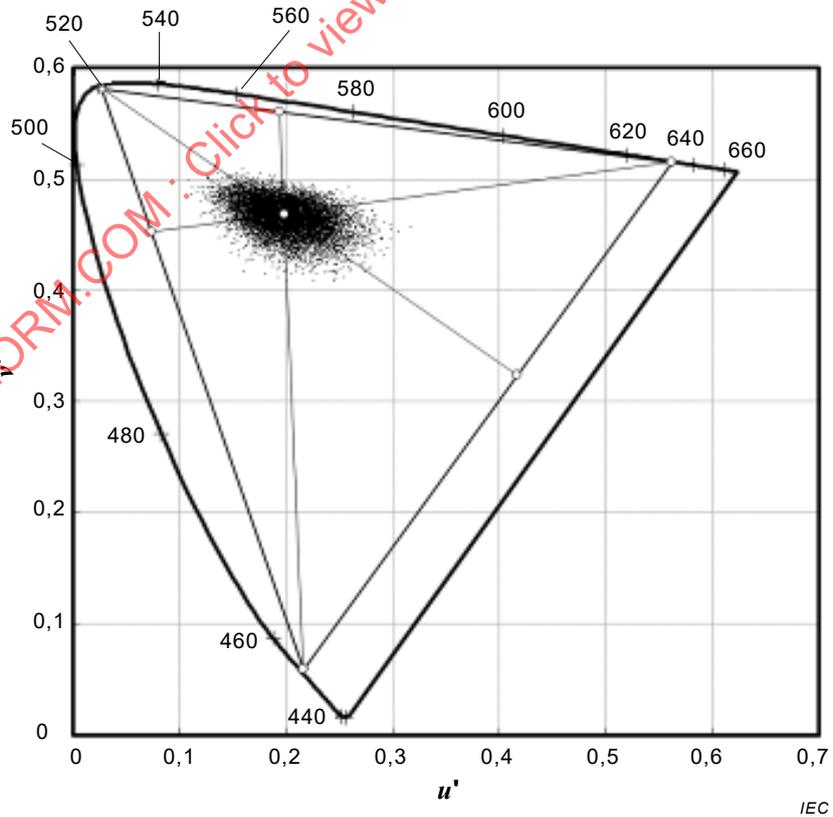


Figure 14 – Colour speckle distribution for  $C_{S-B} = 9,2 \%$ ,  $C_{S-G} = 19,2 \%$ ,  $C_{S-R} = 23,2 \%$  obtained by method (a)

The values of the metrics calculated for the examples in Figure 11 to Figure 14 are shown in Table 2. The comparison between methods (a) and (b) agree quite well for both examples, implying that both methods are consistently valid for evaluating colour speckle behaviour.

**Table 2 – Values of measurement metrics for the examples in Figure 11 to Figure 14**

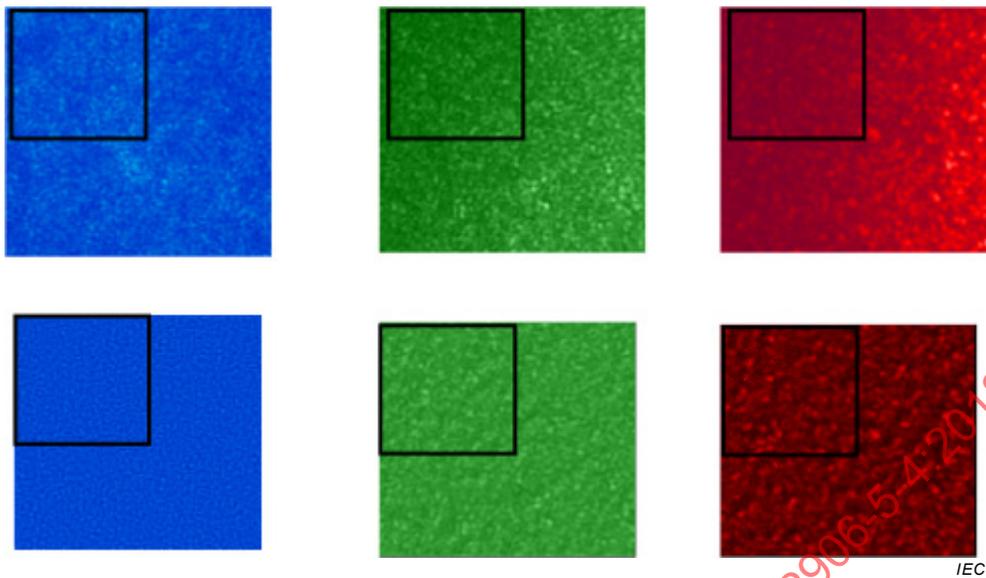
$C_{s-B}$	$C_{s-G}$	$C_{s-R}$	Method /Figure	$u', v'$ variance/covariance			B-GR line		G-BR line		R-BG line		$C_{ps}$
				$\sigma_{u'}^2$	$\sigma_{v'}^2$	$\mu_{u'v'}$	//	⊥	//	⊥	//	⊥	
(%)	(%)	(%)		(10 <sup>-5</sup> )									(%)
9,2	9,7	9,2	(b)/11	16	9	-5	9	15	18	7	14	11	7,3
9,2	9,7	9,2	(a)/13	16	9	-5	9	15	18	6	14	10	7,2
9,2	19,2	23,2	(b)/12	77	20	-15	21	75	73	23	71	25	14,7
9,2	19,2	23,2	(a)/14	78	21	-17	23	77	76	23	73	27	14,9

#### 5.7.4 Elimination of the background effects

In the actual measurement of monochromatic speckle contrast, only the screen speckle shall be measured (see IEC 62906-1-2). Therefore, the measurement area where the background illuminance is uniform shall be chosen. However, the projected speckle (see IEC 62906-1-2) which is an interference pattern projected on a screen is often underlying as background non-uniformity. If the background distribution varies much more slowly than screen speckle, it can be converted into uniform distribution by processing the data after measurement. For example, it is effective to average the local data one by one [2]. For periodic background distributions, the corresponding Fourier component data can be eliminated because the screen speckle is a random process.

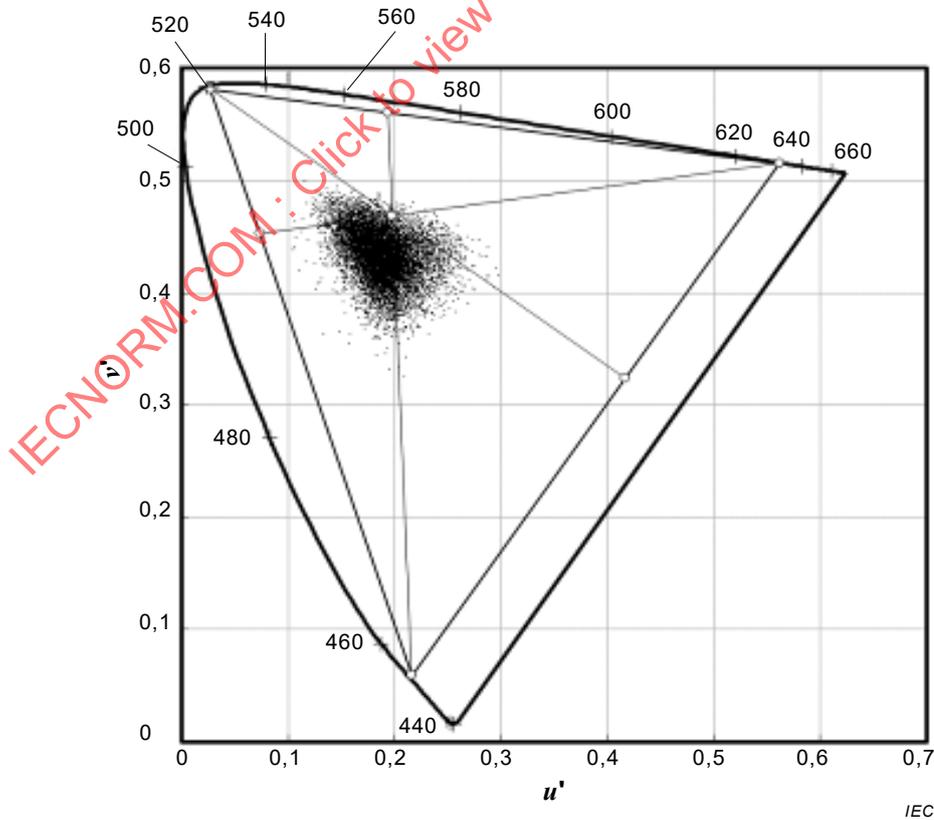
An example of the post-processing for uniform conversion of the background is shown here using the raw data of Figure 12. The raw data of BGR speckle distributions (190 x 196 = 37 240 data) are shown in the upper row of Figure 15 (left: B, centre: G, right: R). The upper-left rectangular regions marked by black lines (100 x 100 = 10 000 data) are used for plotting colour speckle distributions.

In the local area (10 x 10 = 100 data) in the upper-left corner, the raw data are averaged and the data at each point are normalized by the average. This process is repeated by shifting digit by digit. The results are shown in the lower row of Figure 15 (left: B, centre: G, right: R). The underlying background distributions become successfully uniform (flat). The colour speckle distribution in Figure 12 is plotted by superposing the lower row distributions.



**Figure 15 – Raw data of BGR speckle distributions (upper row) and post-processed data (lower row) for BGR monochromatic speckles (left: B, centre: G, right: R)**

The above post-process of the measured data for eliminating the effects of the undesired background distributions shall be indispensable if the background distribution is not uniform. If the raw data shown in the upper row of Figure 15 are directly used for obtaining colour speckle distribution, the results of the measurement would not be correct. Figure 16 is the colour speckle distribution when the raw data are used without any post-processing techniques.



**Figure 16 – Colour speckle distribution directly using the raw data in Figure 15**

The colour speckle distribution is off-centred and protruding towards the B-point compared with the distribution in Figure 12 and Figure 14. The monochromatic BGR speckle contrasts are calculated to be  $C_{s-B} = 16,2\%$ ,  $C_{s-G} = 17,4\%$ ,  $C_{s-R} = 17,3\%$ . The shape of the distribution and the speckle contrast values are obviously different from the post-processed results.

Figure 17 illustrates the colour speckle distribution for  $C_{s-B} = 16,2\%$ ,  $C_{s-G} = 17,4\%$ ,  $C_{s-R} = 17,3\%$  obtained by method (a). The colour speckle distributions between methods (a) and (b) do not agree. The colour speckle metrics are shown in Table 3. The values obtained by methods (a) and (b) do not agree either.

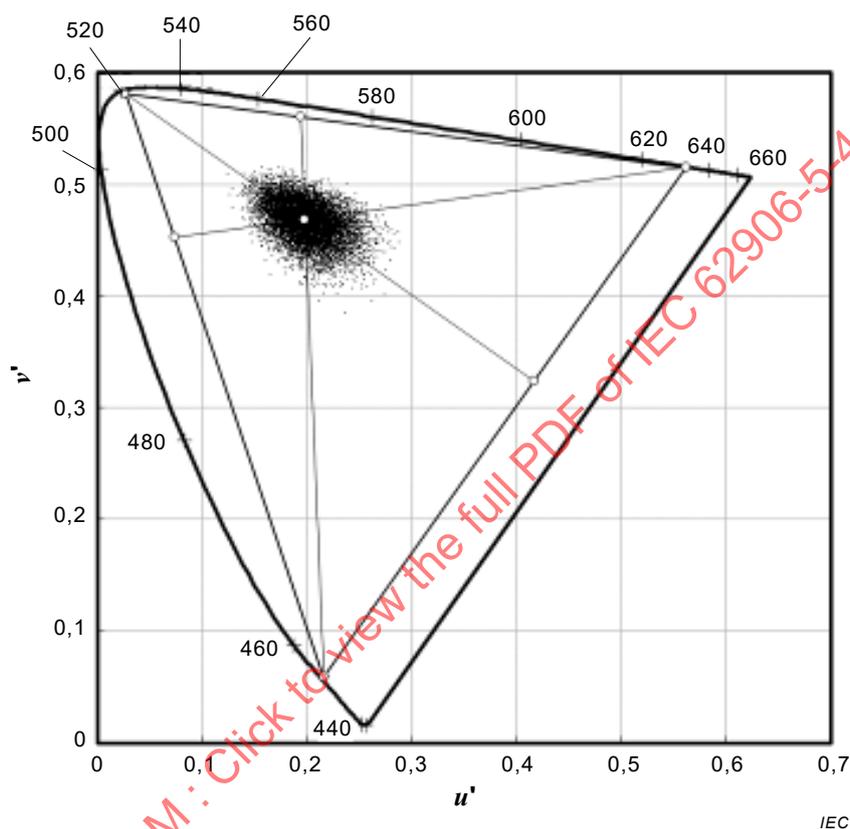


Figure 17 – Colour speckle distribution for  $C_{s-B} = 16,2\%$ ,  $C_{s-G} = 17,4\%$ ,  $C_{s-R} = 17,3\%$  obtained by indirect measuring method (a)

Table 3 – Values of measurement indices for the examples in Figure 16 and Figure 17

$C_{s-B}$	$C_{s-G}$	$C_{s-R}$	Method /Figure	$u', v'$ variance/covariance			B-GR line		G-BR line		R-BG line		$C_{ps}$		
				$\sigma_{u'}^2$	$\sigma_{v'}^2$	$\mu_{u'v'}$	//	⊥	//	⊥	//	⊥			
				(10 <sup>-5</sup> )											(%)
(%)	(%)	(%)													(%)
16,2	17,4	17,3	(b)/16	60	50	-19	51	58	74	36	55	55	14,0		
16,2	17,4	17,3	(a)/17	53	28	-16	30	52	60	21	49	33	13,2		

The average values in the upper-left region (100 x 100 = 10 000 sampling data) are larger for B, smaller for G and much smaller for R than the average of the whole raw data (190 x 196 = 37 240) in Figure 15. Therefore, the centre of the distribution does not agree with the target chromaticity. The overestimated B speckle contrast and the underestimated G and R speckle contrasts and the gradual variations of the background make the distribution protrude irregularly towards the B-point.

The comparison between methods (a) and (b) is quite useful for verifying whether the process of eliminating the background effects works well or not.

### 5.8 Error analysis based on data size

Speckle is a statistical process caused by interference of coherent or partially-coherent lights, which inherently has errors under the law of large numbers. Therefore, the measurement errors increase if the data size becomes smaller [4].

The average of the colour speckle distributions, the normalized photometric distributions, or the normalized monochromatic speckle distributions, in theory, converges on the target chromaticity or unity. However, the average would not exactly converge on these values with larger errors if the data size is smaller, or speckle contrast is larger [4]. The average of the colour speckle distributions and the average of the normalized photometric speckle distributions for speckle contrast values for all BGR colours,  $C_{s-B} = C_{s-G} = C_{s-R} = 80\%$  a),  $60\%$  b),  $40\%$  c), and  $20\%$  d) are plotted with respect to data size in a) Figure 18 and Figure 19, b) Figure 20 and Figure 21, c) Figure 22 and Figure 23, and d) Figure 24 and Figure 25, respectively. The average values are calculated ten times for a data size value to reveal their reproducibility.

a)  $C_{s-B} = C_{s-G} = C_{s-R} = 80\%$

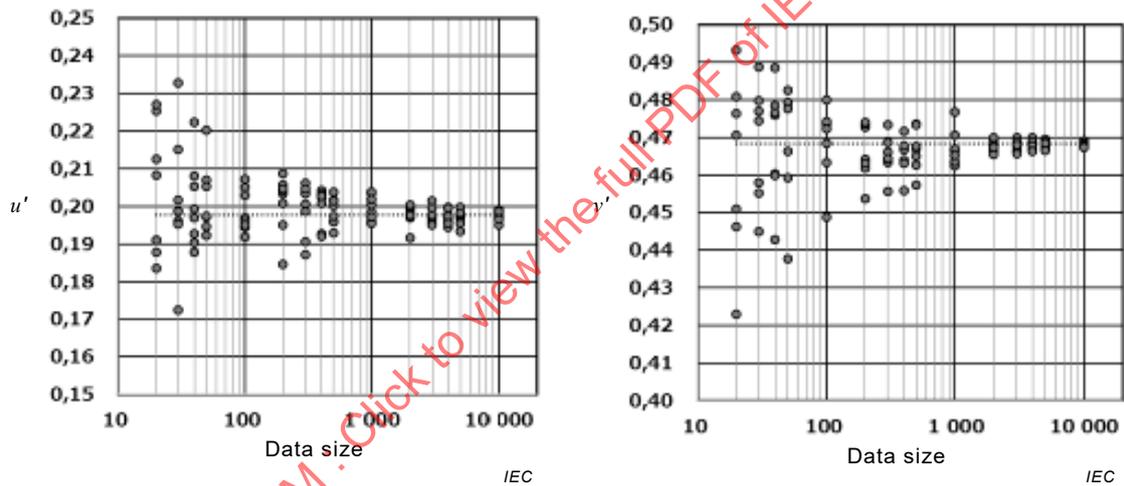
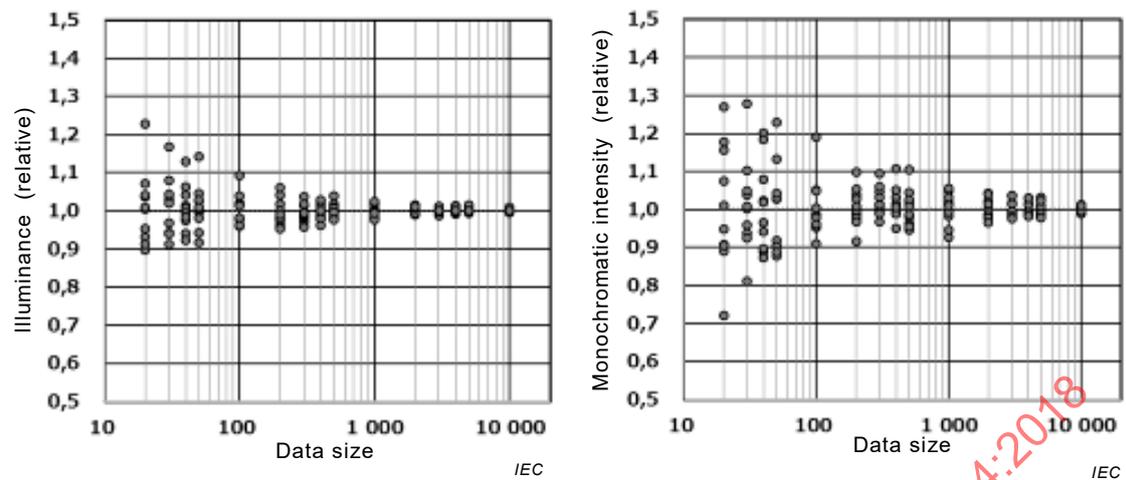
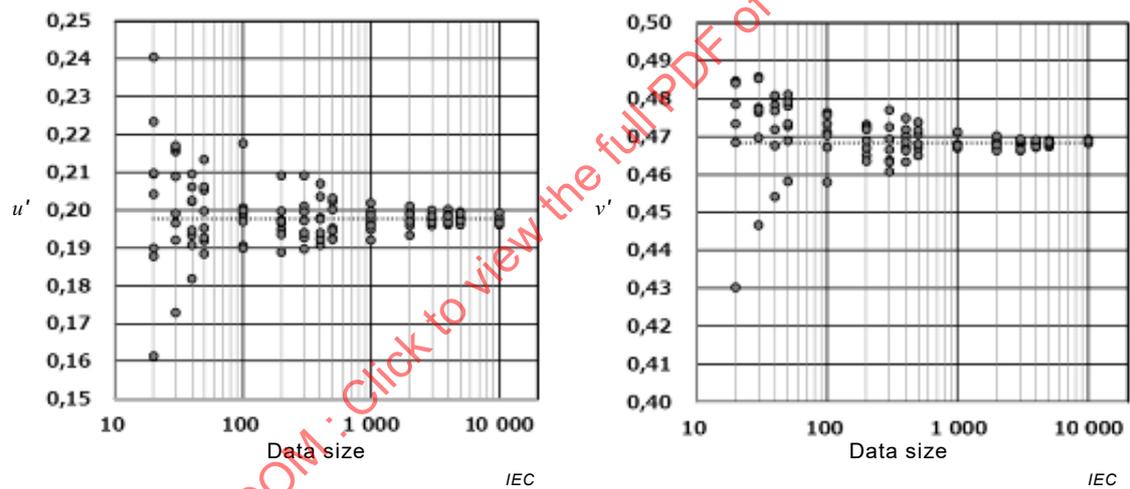


Figure 18 – Calculated average chromaticity values of the colour speckle distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 80\%$



**Figure 19 – Calculated average values of the normalized speckle illuminance speckle distribution and the normalized monochromatic speckle intensity distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 80\%$**

b)  $C_{s-B} = C_{s-G} = C_{s-R} = 60\%$



**Figure 20 – Calculated average chromaticity values of the colour speckle distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 60\%$**

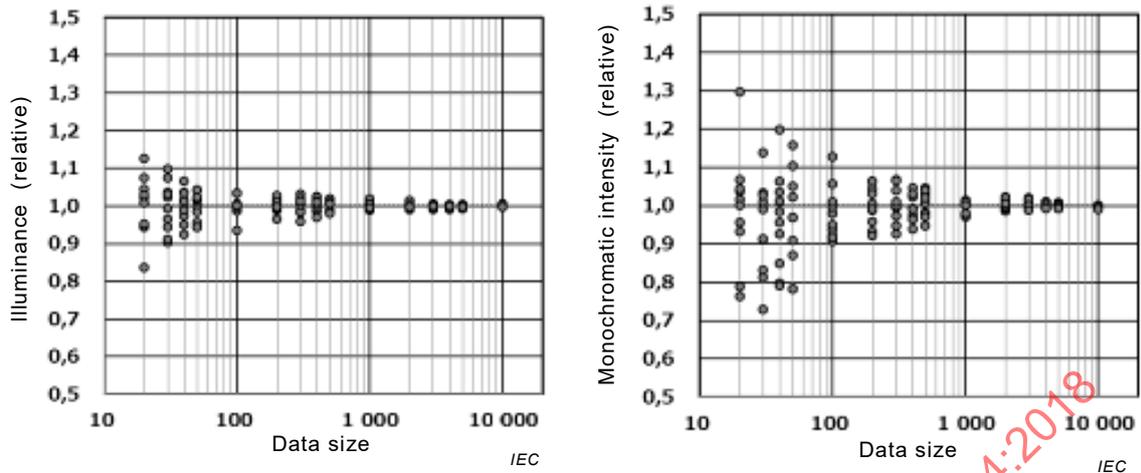


Figure 21 – Calculated average values of the normalized speckle illuminance speckle distribution and the normalized monochromatic speckle intensity distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 60\%$

c)  $C_{s-B} = C_{s-G} = C_{s-R} = 40\%$

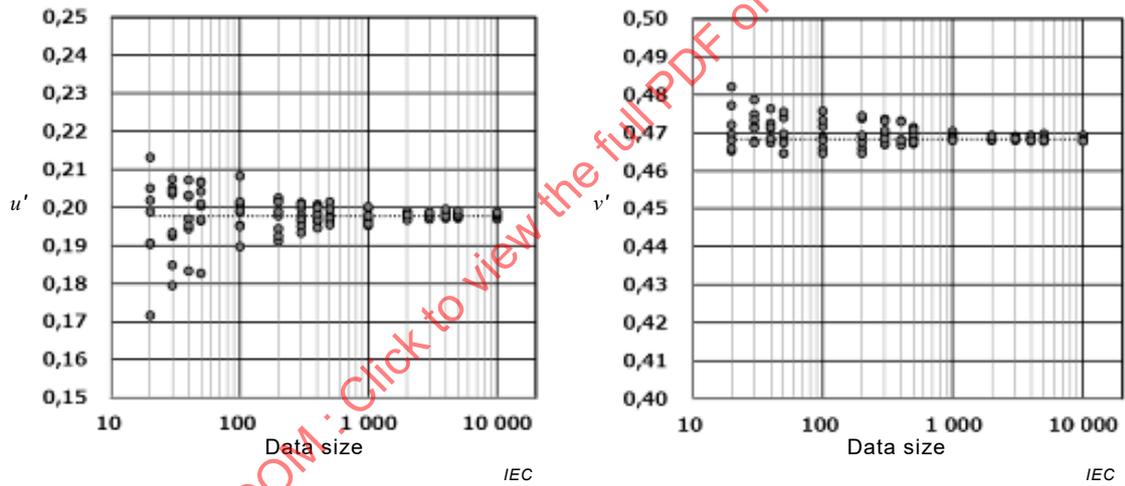


Figure 22 – Calculated average chromaticity values of the colour speckle distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 40\%$

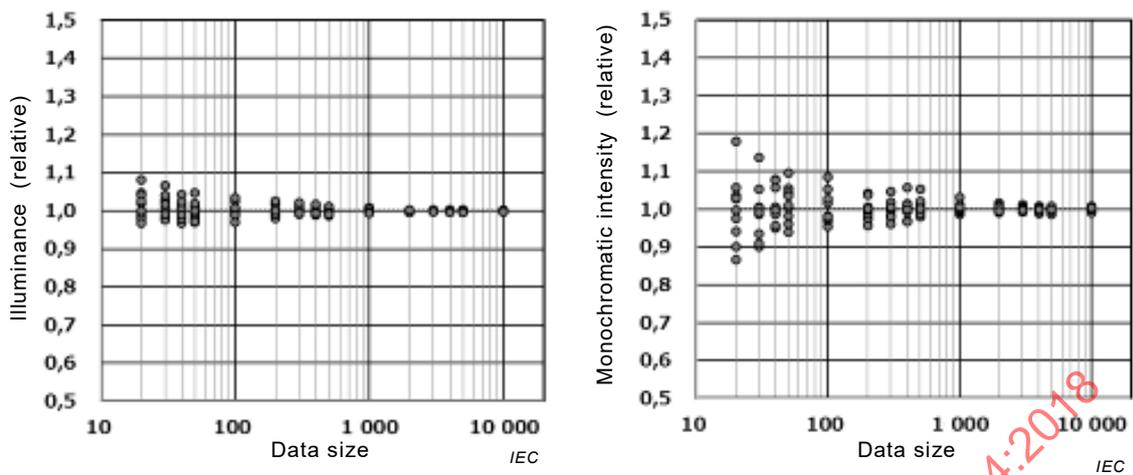


Figure 23 – Calculated average values of the normalized speckle illuminance speckle distribution and the normalized monochromatic speckle intensity distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 40\%$

d)  $C_{s-B} = C_{s-G} = C_{s-R} = 20\%$

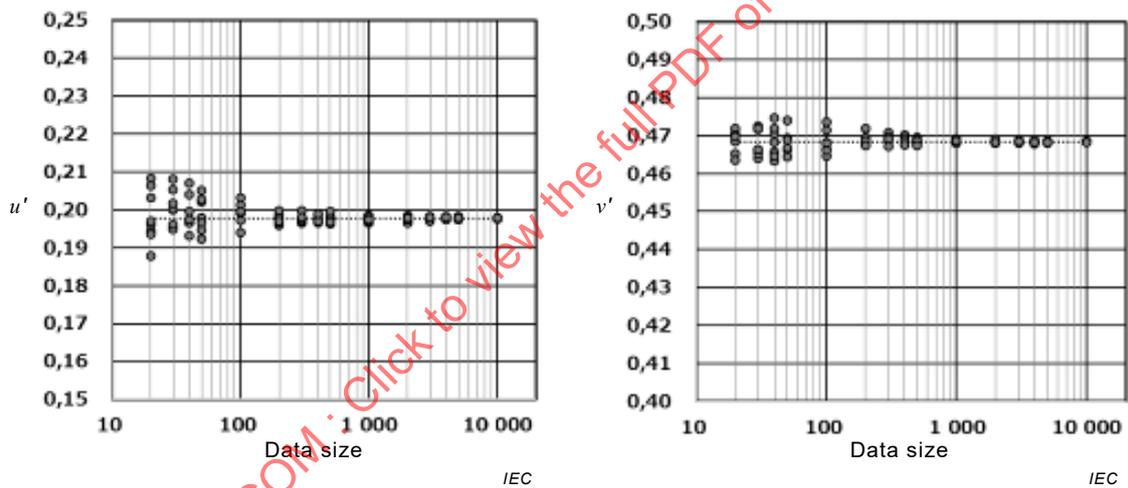
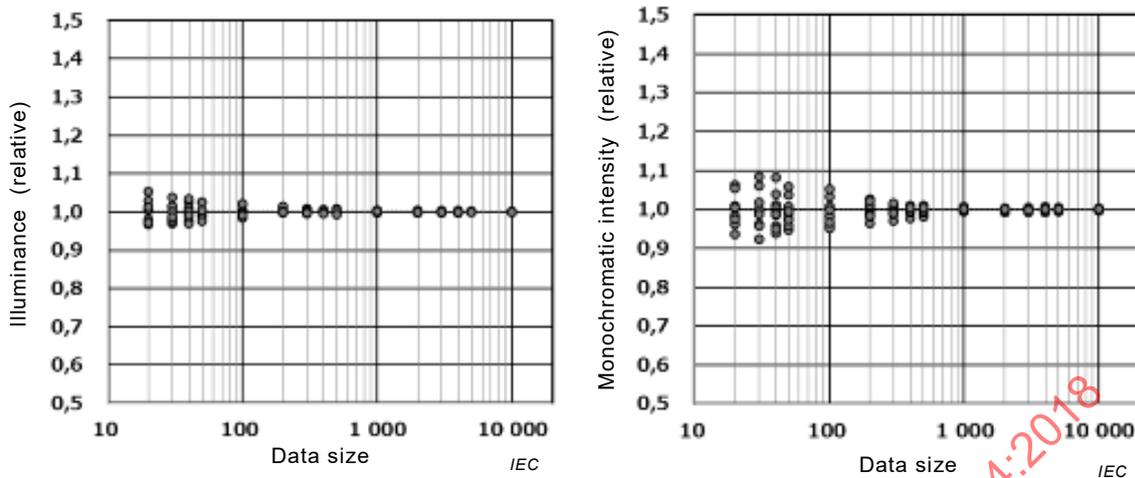


Figure 24 – Calculated average chromaticity values of the colour speckle distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 20\%$



**Figure 25 – Calculated average values of the normalized speckle illuminance speckle distribution and the normalized monochromatic speckle intensity distribution with respect to data size for  $C_{s-B} = C_{s-G} = C_{s-R} = 20\%$**

When the data size = 10 000, the ten-times trials always converge on the target chromaticity and unity. The 10 000-data size is sufficient for keeping reproducibility with small errors. All the examples of colour speckle distribution shown in this document are based on the data size of 10 000 to keep reproducibility.

When the data size = 1 000, the ten-times trials scatter to some degree in case of  $C_{s-B} = C_{s-G} = C_{s-R} = 80\%$ . However, the ten-times trials are approximately converging on the target chromaticity and unity if  $C_{s-B}$ ,  $C_{s-G}$  and  $C_{s-R}$  are less than 60 %.

When the data size = 100, the ten-times trials scatter more than  $\pm 0,01$  in chromaticity and  $\pm 10\%$  in the normalized illuminance and intensity if  $C_{s-B}$ ,  $C_{s-G}$  and  $C_{s-R}$  are more than 60 %. Around  $C_{s-B} = C_{s-G} = C_{s-R} = 20\%$ , the ten-times trials scatter less than  $\pm 0,005$  in chromaticity and  $\pm 5\%$  in the normalized illuminance and intensity. The local averaging area of  $10 \times 10 = 100$  data used for eliminating the background effects in [2] makes sense when  $C_{s-B}$ ,  $C_{s-G}$  and  $C_{s-R}$  are less than 20 %. For larger speckle contrasts, local averaging of the  $10 \times 10$  area should be repeated to reduce the errors.

It should be noted that the monochromatic and colour speckles, more or less, affect the errors in the conventional photometric and colourimetric measurements because the spatially-fine speckle patterns are averaged in the measurements. If speckle contrasts are low enough and the data size is large enough, the results of the conventional measurements would be approximately correct. However, the speckles will significantly affect the measurements if speckle contrasts are higher and the data size is smaller. The error analysis in 5.8 shall be considered for such cases.

## 6 Direct measuring methods of colour speckle

### 6.1 General

Clause 6 specifies the direct measuring methods of colour speckle.

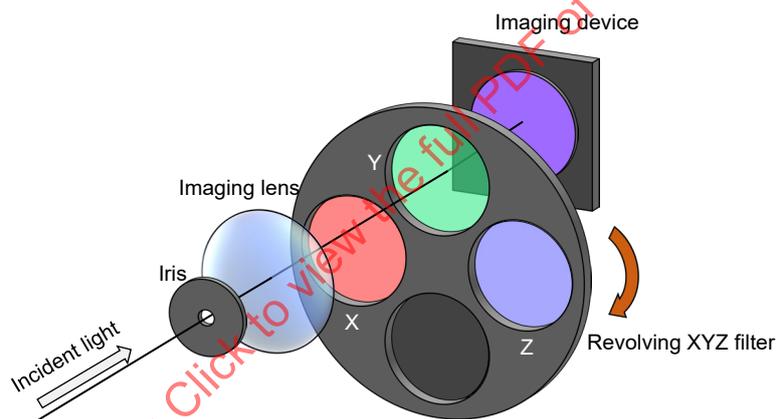
The same standard measuring conditions as specified in IEC 62906-5-2 shall also be applied to the colour speckle measurement.

## 6.2 Fundamental design of LMD for colour speckle measurement

Subclause 6.2 specifies the fundamental design of the LMD for directly measuring colour speckle. The LMD for directly measuring colour speckle shall have basically the same requirements as the LMD for measuring monochromatic speckle contrast (see IEC 62906-5-2), except for the optical filters set in front of the sensor. Each spectral transmittance of the filters is equivalent to the colour matching function, or to the filtering of B, G, R power to obtain the tristimulus values  $X$ ,  $Y$ ,  $Z$ . Sensor pixels smaller than the grain size of the speckle should be used for accurate measurements. The above requirements are summarized as follows.

- The MTF of the optics shall be equivalent to the human eye.
- The sensor shall include a colorimetric optic equivalent to the human eye.
- The outputs for colorimetric and photometric calculation or the calculated results shall be provided.

Figure 26 illustrates an example of the LMDs using XYZ filters for colour speckle measurement [5]. The outputs of this LMD are the 2D map of tristimulus values  $X$ ,  $Y$ ,  $Z$ . At each point of the 2D map, chromaticity coordinates  $u'$ ,  $v'$  are calculated using the  $X$ ,  $Y$ ,  $Z$  values of Formula (7).

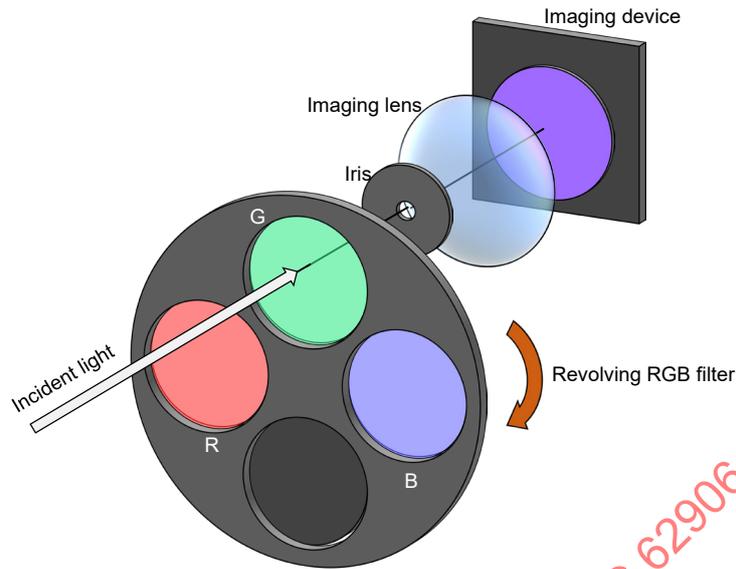


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**Figure 26 – Example of LMDs using XYZ filters for colour speckle measurement**

Each XYZ filter has a spectral transmittance equivalent to the colour matching function, the XYZ filters rotating in turn to the position of the optical axis. The 2D spatial maps are obtained for the tristimulus values  $X$ ,  $Y$ ,  $Z$ .

Figure 27 illustrates an example of the LMDs using BGR filters. The outputs of this LMD are the 2D maps of the projected power for each BGR colour of the input light at arbitrary chromaticity points including the reference white. At each point of the 2D map, chromaticity coordinates  $u'$ ,  $v'$  are obtained using the  $X$ ,  $Y$ ,  $Z$  values calculated using the ideal colour matching functions as in the method in 5.7.



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**Figure 27 – Example of LMDs using BGR filters for colour speckle measurement**

**6.3 Colour speckle measuring method using LMD with XYZ filters**

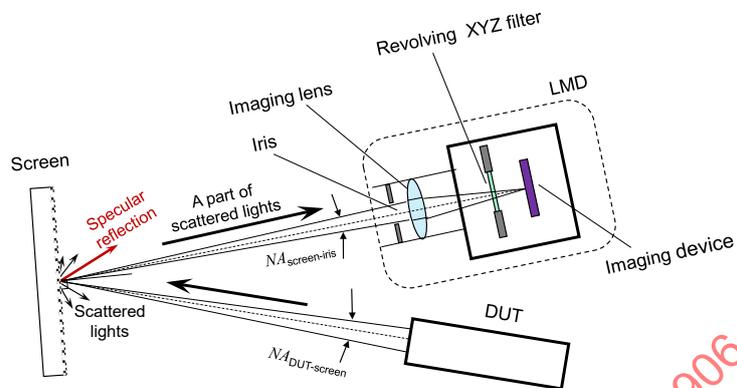
Figure 28 shows an example of the measurement geometries using an LMD with XYZ filters (see Figure 26) for colour speckle in a front-projection type LDD. The details of the colour speckle measurement procedure shown below shall be applied unless otherwise specified.

- a) Place the DUT in front of the screen. The projection distance should be the same as the nominal product design values.
- b) Place the LMD using the XYZ filters as indicated in Figure 28. The measurement distance should be the same as the intended audience viewing distance. The imaging device shall be placed at the conjugate focal plane of the screen.
- c) Adjust the DUT to project a pattern of the target chromaticity (e.g., the reference white, see 5.3).
- d) Project the pattern. The size shall be larger than the field of view of the LMD. The spatial uniformity can be calibrated as in 5.7.4.
- e) Focus the LMD on the projected pattern on the screen, aligning the DUT and LMD at an appropriate angle to avoid specular reflection to the LMD.
- f) Capture the pattern image, adjusting the exposure time to avoid saturation of the imaging device.
- g) Obtain the 2D map of tristimulus values  $X, Y, Z$ , changing the XYZ filters in turn.
- h) Calculate the chromaticity coordinates  $u', v'$  at each point of the 2D map.
- i) Plot the colorimetric distribution of colour speckle on the CIE 1976 chromaticity diagram.
- j) Visualize the photometric distribution using a histogram, for example.
- k) Calculate the colour speckle metrics, photometric speckle contrast ratio  $C_{ps}$ , variance  $\sigma_u^2$ ,  $\sigma_v^2$  and covariance  $\mu_{u'v'}$ .
- l) Report the pattern properties, such as size, the average chromaticity, the average illuminance, considering the statistical errors explained in 5.8.
- m) Report the above procedures and the results.

To improve the accuracy of the measurement, the errors which occurred due to the difference between the actual spectral transmittance of the XYZ filters and the ideal colour matching

functions should be calibrated appropriately. An example of the calibration method is shown in Annex C.

The above procedure shall be applied to other geometries (e.g., rear projection) in a similar manner.



**Figure 28 – Example of measurement geometries for colour speckle using an LMD with XYZ filters**

#### 6.4 Colour speckle measuring method using LMD with BGR filters

Figure 29 shows an example of the measurement geometries using an LMD with BGR filters (see Figure 27) for colour speckle in a front-projection type LDD. The details of the colour speckle measurement procedure shown below shall be applied unless otherwise specified.

- Place the DUT in front of the screen. The projection distance should be the same as the nominal product design values.
- Place the LMD as indicated in Figure 29. The measurement distance should be the same as the intended audience viewing distance. The imaging device shall be placed at the conjugate focal plane of the screen.
- Adjust the DUT to project a pattern of the target chromaticity (e.g., the reference white, see 5.3).
- Project the pattern. The size shall be larger than the field of view of the LMD. The spatial uniformity can be calibrated as in 5.7.4.
- Focus the LMD on the projected pattern on the screen, aligning the DUT and LMD at an appropriate angle to avoid specular reflection to the LMD.
- Capture the pattern image, adjusting the exposure time to avoid saturation of the imaging device.
- Obtain the 2D map of the projected power for each BGR colour, changing the BGR filters in turn.
- Calculate the chromaticity coordinates  $u'$ ,  $v'$  at each point of the 2D map, using the ideal colour matching functions and the measured BGR spectra, as in the method in 5.2 and 5.7.
- Plot the colorimetric distribution of colour speckle on the CIE 1976 chromaticity diagram.
- Visualize the photometric distribution using a histogram, for example.
- Calculate the colour speckle metrics, photometric speckle contrast ratio  $C_{ps}$ , variance  $\sigma_u^2$ ,  $\sigma_v^2$  and covariance  $\mu_u v'$ .
- Report the pattern properties, such as size, the average chromaticity, the average illuminance, considering the statistical errors explained in 5.8.
- Report the above procedures and the results.

The above procedure shall be applied to other geometries (e.g., rear projection) in a similar manner.

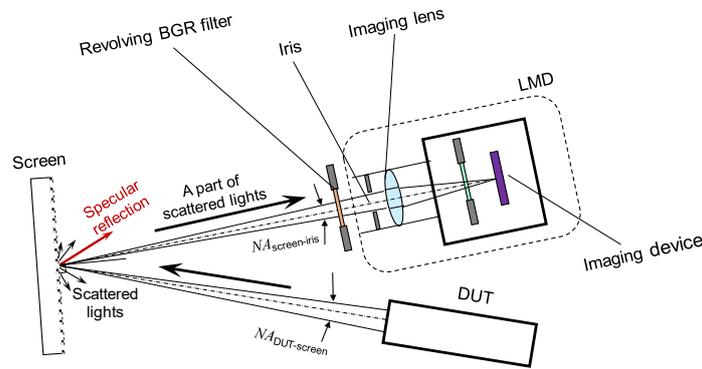


Figure 29 – Example of measurement geometries for colour speckle using an LMD with BGR filters

## 7 Measuring methods related to spatial variation

### 7.1 General

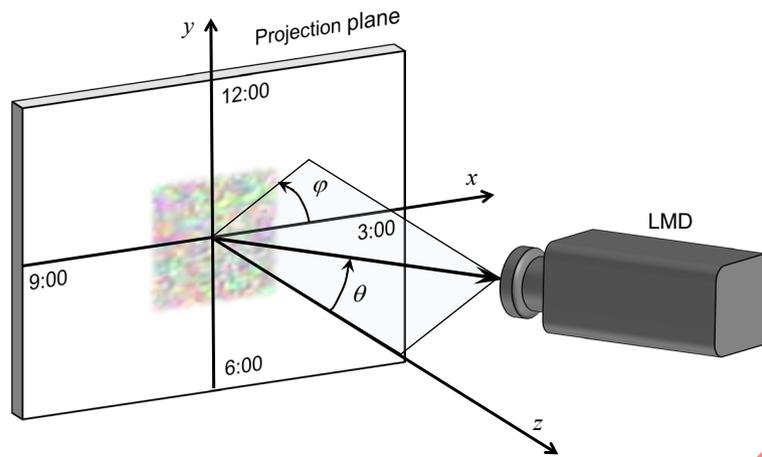
Clause 7 specifies the measuring methods related to spatial variation at the points of the projection plane (screen).

The standard measuring conditions and standard conditions of the measuring equipment specified in IEC 62906-5-2 shall apply.

### 7.2 Angular colour speckle variation

The angular performance of the photometric speckle contrast (including the monochromatic speckle contrast) and colour speckle distribution (variance/covariance) shall be measured at angles of  $(0^\circ, 0^\circ)$ ,  $(\theta, 0^\circ)$ ,  $(\theta, 90^\circ)$ ,  $(\theta, 180^\circ)$  and  $(\theta, 270^\circ)$  in the polar coordinate system  $(\varphi, \theta)$  defined in IEC 62906-5-2.

The azimuth angle  $\varphi$  should be measured in the counter-clockwise direction as in Figure 30. It is related to the directions on a clock face as follows:  $\varphi = 0^\circ$  is the 3-o'clock direction ("right"),  $\varphi = 90^\circ$  the 12-o'clock direction ("top"),  $\varphi = 180^\circ$  the 9-o'clock direction ("left") and  $\varphi = 270^\circ$  the 6-o'clock direction ("bottom"). Measurement at additional angles should be carried out if necessary.



**Figure 30 – Representation of the viewing direction, or direction of measurement, defined by the angle of inclination  $\theta$ , and the angle of rotation (azimuth angle  $\varphi$ ) in a polar coordinate system**

### 7.3 Photometric speckle contrast uniformity/non-uniformity

Photometric speckle contrast non-uniformity,  $NU_{ps}$  is a metric of how well the photometric speckle contrast remains constant over the image area on the projection plane.

Photometric speckle contrast shall be measured at the standard positions of the measurement field (projected active image area). The standard positions shall be in common with the fundamental optical measurements of the laser display devices. Any other position layout shall be reported.

The measurement shall be carried out at the angle normal to the screen. However, the other angles should be measured and reported for certain purposes.

Photometric speckle contrast non-uniformity,  $NU_{ps}$ , shall be calculated using the following formula unless otherwise specified.

$$NU_{ps} = \frac{\max(C_{ps(i)}) - C_{ps(a)}}{C_{ps(a)}} \quad (10)$$

where

$C_{ps(a)}$  is the average colour speckle contrast value calculated as:

$$C_{ps(a)} = \sum_{i=1}^N \frac{C_{ps(i)}}{N} \quad (11)$$

where

$N$  is the number of measurement points,

$C_{ps(i)}$  is the photometric speckle contrast of the  $i^{\text{th}}$  measurement point.

The formulae shall be reported if other formulae are applied.

#### 7.4 Colour speckle variance/covariance non-uniformity

Colour speckle variance/covariance non-uniformity  $NU_{\text{csu}'}$ ,  $NU_{\text{csv}'}$ ,  $NU_{\text{csu}'\text{v}'}$  shall be measured based on CIE 1976 chromaticity between the centre and the other points on the image projected area.

The standard measurement positions shall be in common with the fundamental optical measurements of the laser display devices. Any other position layout shall be reported.

The measurement shall be carried out at the angle normal to the screen. However, the other angles should be measured and reported for certain purposes.

The following formulae shall be used for calculating colour speckle variance/covariance non-uniformity  $NU_{\text{csu}'}$ ,  $NU_{\text{csv}'}$ ,  $NU_{\text{csu}'\text{v}'}$  unless otherwise specified.

$$NU_{\text{csu}'} = \max(\sigma_{\text{u}'(i)}^2 - \sigma_{\text{u}'(\text{centre})}^2)$$

$$NU_{\text{csv}'} = \max(\sigma_{\text{v}'(i)}^2 - \sigma_{\text{v}'(\text{centre})}^2)$$

$$NU_{\text{csu}'\text{v}'} = \max(\mu_{\text{u}'\text{v}'(i)} - \mu_{\text{u}'\text{v}'(\text{centre})}) \tag{12}$$

NOTE The symbol  $i$  implies the measured value of the  $i^{\text{th}}$  measurement point.

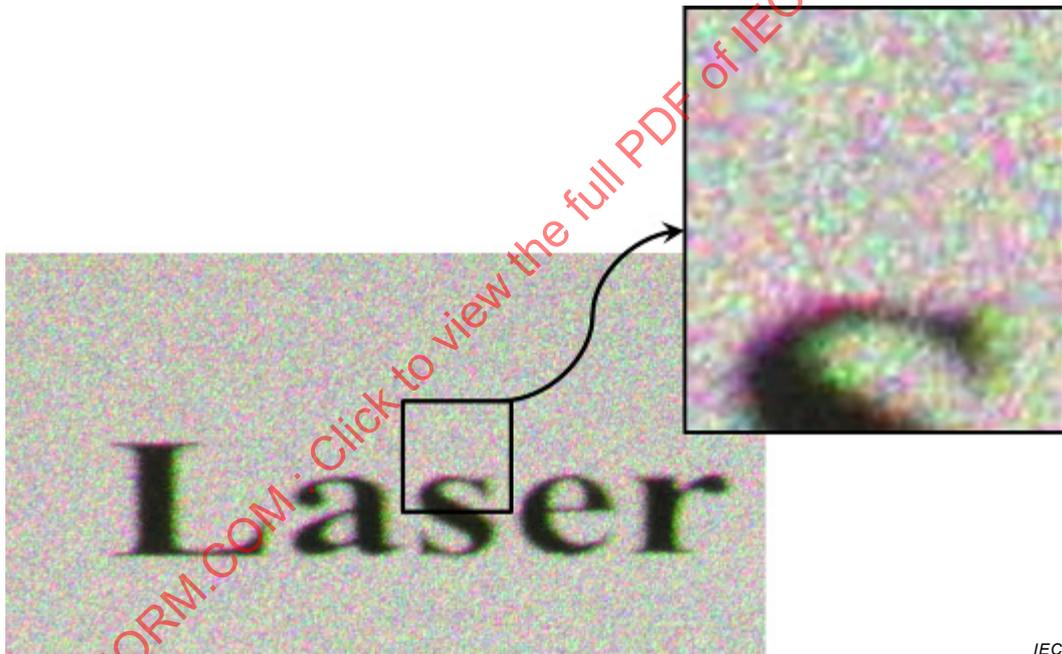
The formulae shall be reported if other formulae are applied.

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## Annex A (informative)

### Complementary explanation of colour speckle

Colour speckle of laser display devices (LDDs) is defined as speckle when the light source is multi-coloured (see IEC 62906-1-2). It is recognized as fine colour patterns different from the colour intended to be displayed. A photograph of typical colour speckle is shown in Figure A.1 for reference. This printed photograph is not the same as the colour speckle on the human retina. The interference of coherent or partially coherent light in the human eye produces shinier spots on the retina. For scientific accuracy, the optics of the camera shall have an MTF equivalent to the human eye system. That is, the colour speckle discussed in this document is the colour version of the screen speckle which is defined as subjective speckle arising from the scattering or diffusion of coherent or partially coherent light on a screen (see IEC 62906-1-2). The screen speckle is a fine random pattern which changes with a slight change of the eye position. It is necessary, when measuring the screen speckle, to use a particularly-designed equipment with an MTF equivalent to the human eye optics.



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Figure A.1 – Photograph of colour speckle

## Annex B (informative)

### Examples of colour speckle distributions

#### B.1 Colour speckle distributions (one of the BGR: 90 %, the others: 1 %)

Examples of colour speckle distributions and photometric speckle distributions when the speckle contrast of one of the primary colours is 90 % and the others are 1 % are shown here.

Figure B.1 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 90\%$ ,  $C_{s-G} = 1\%$ ,  $C_{s-R} = 1\%$ . The reason why speckle contrast of 1 % is used instead of 0 % is to visualize the distribution itself. The distribution is completely aligned on the B-GR line for  $C_{s-G} = 0\%$ ,  $C_{s-R} = 0\%$ . A similar distribution will be obtained for hybrid LDDs using phosphors excited by blue coherent light sources. The photometric speckle distribution is shown in the histogram of Figure B.2. The photometric distribution is dispersed in a very narrow range.

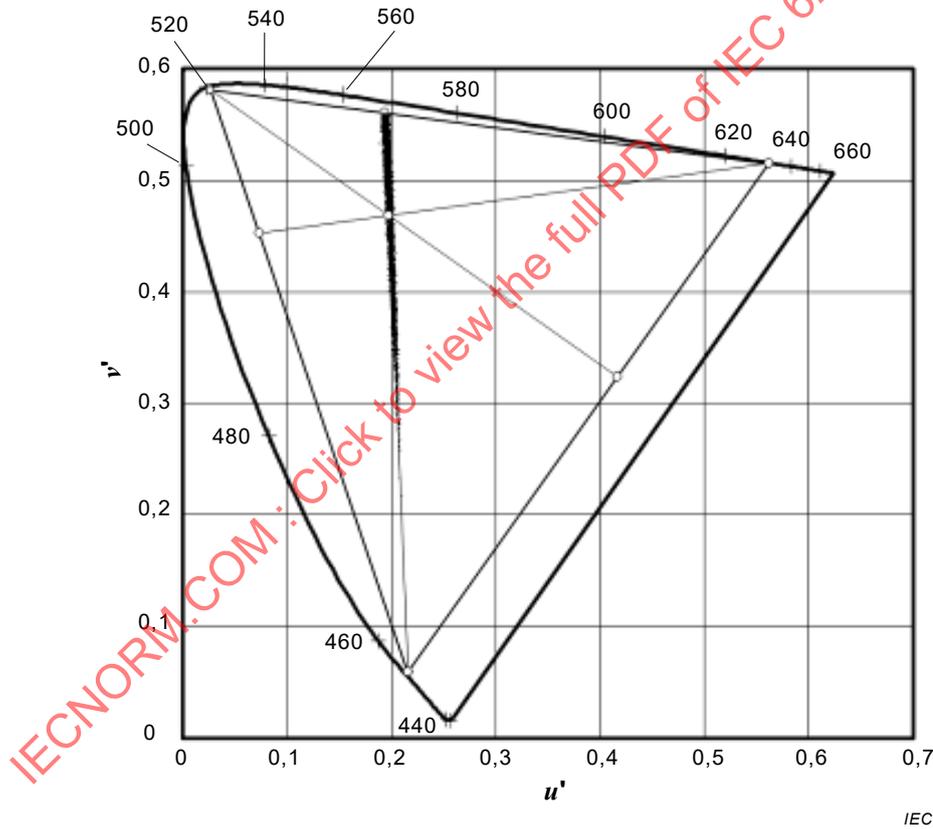
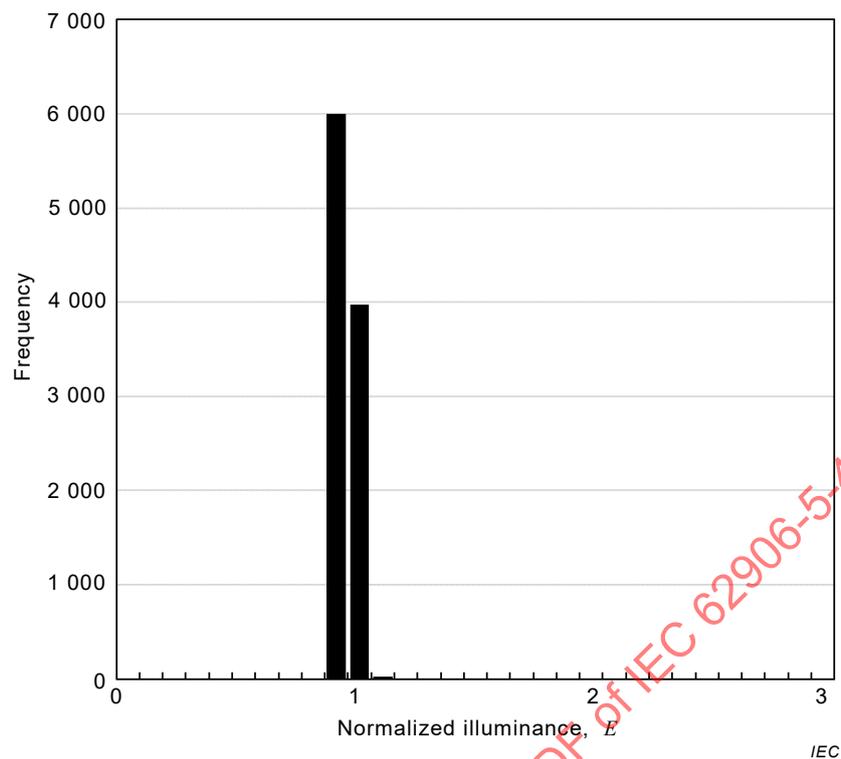


Figure B.1 – Colour speckle distribution for  $C_{s-B} = 90\%$ ,  $C_{s-G} = 1\%$ ,  $C_{s-R} = 1\%$



**Figure B.2 – Photometric speckle distribution for  $C_{s-B} = 90\%$ ,  $C_{s-G} = 1\%$ ,  $C_{s-R} = 1\%$**

Figure B.3 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 1\%$ ,  $C_{s-G} = 90\%$ ,  $C_{s-R} = 1\%$ . The distribution is almost aligned on the G-BR line. The photometric speckle distribution is shown in the histogram of Figure B.4. However, the photometric distribution is dispersed much more widely than in Figure B.2. This is because colour speckle distribution spreading towards the high luminous sensitivity G point decisively affects the photometric distribution. Figure B.5 illustrates a colour speckle distribution in the CIE 1976 chromaticity diagram for the case where  $C_{s-B} = 1\%$ ,  $C_{s-G} = 1\%$ ,  $C_{s-R} = 90\%$ . The distribution is almost aligned on the R-BG line. The photometric speckle distribution is shown in the histogram of Figure B.6. The photometric distribution is dispersed in a range wider than in Figure B.2 and narrower than in Figure B.4. The photometric distribution strongly depends on the luminous sensitivity of the primary colour of which the speckle contrast is dominantly large.

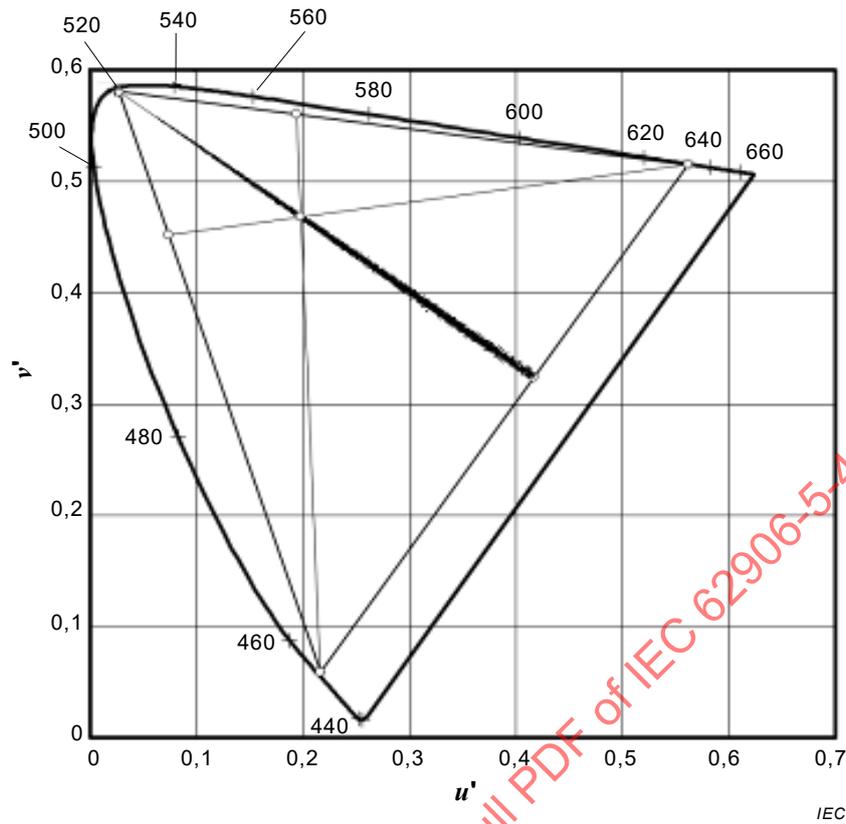


Figure B.3 – Colour speckle distribution for  $C_{S-B} = 1\%$ ,  $C_{S-G} = 90\%$ ,  $C_{S-R} = 1\%$

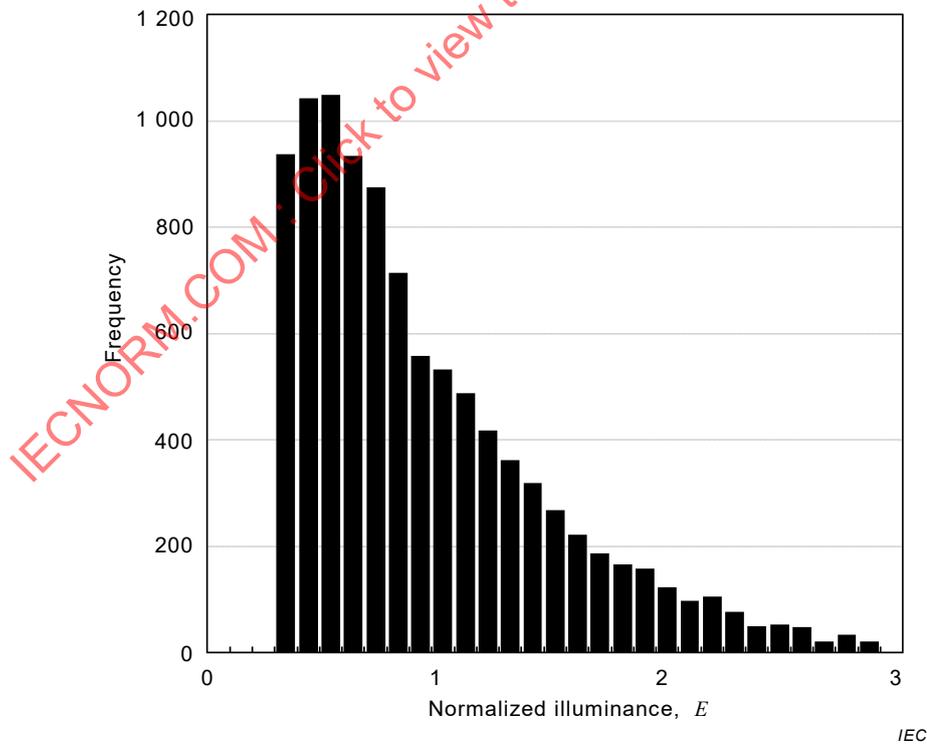


Figure B.4 – Photometric speckle distribution for  $C_{S-B} = 1\%$ ,  $C_{S-G} = 90\%$ ,  $C_{S-R} = 1\%$