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Graphic technology and photography — Colour characterization of digital still cameras (DSCs) —

Part 4:
Programmable light emission system

Technologie graphique et photographie — Caractérisation de la couleur des appareils photonumériques —

Partie 4: Système d'émission de lumière programmable

Reference number
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Foreword

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The committee responsible for this document is ISO/TC 42, *Photography*.

ISO 17321 consists of the following parts, under the general title *Graphic technology and photography — Colour characterization of digital still cameras (DSCs)*:

— *Part 1: Stimuli, metrology and test procedures*

— *Part 2: Considerations for determining scene analysis transforms* [Technical Report]

— *Part 4: Programmable light emission system* [Technical Specification]

The following parts are under preparation:

— *Part 3: User controls and readouts for scene-referred imaging applications* [Technical Report]

Introduction

There are many application areas such as medical imaging, cosmetics, e-commerce, sales catalogue, fine art reproduction and artistic archive where colorimetric image capture and colorimetric image reproduction are desired.

A high colour-fidelity imaging system using a black-and-white digital camera with rotary colour filters[12], and digital video cameras specified for colorimetric image capture[13], both of which have the same colour sensitivity as the colour matching functions defined by CIE 1931, are available today and fulfil these requirements. However, Reference [12] is a large-scale device which cannot be used to capture moving objects, and Reference [13] is dedicated to motion picture use.

Digital still cameras (DSCs) are often used as convenient devices for colorimetric image capture. Typically, DSCs do not have sensor sensitivities that are linear transforms of the colour matching functions defined by CIE 1931. It is, therefore, necessary that a matrix conversion from DSC-image-capture data to scene-colorimetric data be done to transform camera image data to estimates of scene colorimetric data. Although there are several methods to derive such a matrix, a method using colour targets is the most common when there is no data describing the DSC sensor spectral sensitivities.

Colour targets used to derive this conversion matrix are X-Rite ColorChecker Classic®[1], X-Rite ColorChecker Digital SG®[2] and others. These targets are reflective and so have a limited colour gamut compared to scenes where the subject includes highly saturated colours. In such a case, colour targets with highly saturated colours that can be used to derive the colour conversion matrix are very useful.

This part of ISO 17321 is applicable to light emitting devices such as inorganic or organic LEDs, quantum dots and laser diodes.

Note that although an integrating sphere is typically used, other mechanisms would also be applicable.

A procedure using a nonlinear Generalized Reduced Gradient (GRG) algorithm is specified in this part of ISO 17321 to minimize the square of the difference between a desired colour spectrum and the colour spectrum of the programmable light emission system.

This part of ISO 17321 will make use of a metric (S_{R2}), which provides a simple and direct means to calculate the colour difference between two spectra. This criterion (S_{R2}) will be used as a method to evaluate the performance of a programmable light emission system in terms of its ability to match a reference spectral power distribution. S_{R2} and CIEDE2000 metrics are both used for colour target evaluation.

This programmable light emission system can generate arbitrary illuminants such as D55, D65 and Illuminant A. Annex D describes evaluation metrics for light sources.

This system has several advantages as follows.

- An arbitrary smooth spectral power distribution similar to colour targets under a light source can be produced.
- Many colour metamers can be generated easily.
- Colours with different luminance, same hue and same saturation can be generated easily.
- Colours with different saturation, same luminance and same hue can be generated easily.
- Colours with high luminance can be produced.
- Reference colour target can be provided for display systems.

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[1] ColorChecker Classic® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

[2] ColorChecker Digital SG® is an example of a suitable product available commercially. This information is given for the convenience of users of this document and does not constitute an endorsement by ISO of this product.

International Organization for Standardization

Graphic technology and photography — Colour characterization of digital still cameras (DSCs) —

Part 4:
Programmable light emission system

1 Scope

This part of ISO 17321 specifies requirements for a programmable light emission system to produce various spectral radiance distributions intended for DSC colour characterization applications.

NOTE 1 Evaluation metrics are described in this part of ISO 17321. These evaluations metrics are intended to provide “Figure of Merit (goodness)” relating to the ability of the device to produce arbitrary spectral power distributions.

NOTE 2 This part of ISO 17321 applies to a programmable light emission system composed of LEDs. However, it can be applied to light emitting devices such as quantum dots, organic LEDs, laser diodes and so forth.

NOTE 3 If spiky spectral reproduction is required, devices which have more spiky spectral light emission are intended to be used.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7589, *Photography — Illuminants for sensitometry — Specifications for daylight, incandescent tungsten and printer*

3 Terms and definitions

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

3.1
colour matching functions
tristimulus values (3.6) of monochromatic stimuli of equal radiant power

[SOURCE: CIE Publication 17.4, 845-03-23]

3.2
colour rendering index [R]
measure of the degree to which the psychophysical colour of an object illuminated by a test illuminant conforms to that of the same object illuminated by the reference illuminant, suitable allowance having been made for the state of chromatic adaptation

[SOURCE: CIE Publication No. 17.4:1987, 845-02-61]

3.3
digital still camera
DSC
device which incorporates an image sensor and which produces a digital signal representing a still picture

Note 1 to entry: A digital still camera is typically a portable, hand-held device. The digital signal is usually recorded on a removable memory, such as a solid-state memory card or magnetic disk.

[SOURCE: ISO 17321-1:2012, 3.2]

3.4
light-emitting diode
LED
semiconductor diode that emits non coherent optical radiation through stimulated emission resulting from the recombination electrons and photons, when excited by an electric current

[SOURCE: IEC 60050-521, 521-04-39]

3.5
raw DSC image data
image data produced by or internal to a DSC that has not been processed, except for A/D conversion and the following optional steps: linearization, dark current/frame subtraction, shading and sensitivity (flat field) correction, flare removal, white balancing (e.g. so the adopted white produces equal RGB values or no chrominance), missing colour pixel reconstruction (without colour transformations).

[SOURCE: ISO 17321-1:2012:3.4 — modified.]

3.6
tristimulus values
amount of the three reference colour stimuli, in a given trichromatic system, required to match the colour of the stimulus considered

Note 1 to entry: See *colour matching functions* (3.1).

[SOURCE: CIE Publication 17.4, 845-03-22]

4 Requirements

4.1 General

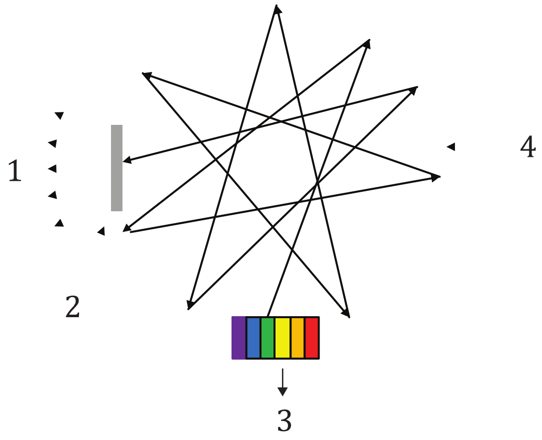
Figure 1 shows a section of an integrating sphere. This sphere is one method to ensure good spatial uniformity. Light emitting devices are placed at the bottom and an output window is placed on the side to allow the mixed light to be emitted. Annex A shows a typical LED-driving method.

NOTE 1 Integrating sphere is a typical case, but other mechanisms would be applicable.

There are many kinds of light emitting devices. However, this part of ISO 17321 describes a programmable light emission system using typical LEDs. Figure 2 shows typical spectral power distributions of a number of LEDs. These LEDs will be intensity-modulated and mixed (integrated) to produce a required spectral power distribution.

NOTE 2 Pulse width and interval modulation for intensity modulation is applicable.

NOTE 3 DSCs with automatic exposure control and automatic white balance cannot be applied for colour calibration using this system.



Key

1	uniform light emission on the output window
2	output window
3	light emitting device array
4	integrating sphere

Figure 1 — Schematic configuration of the programmable light emission system

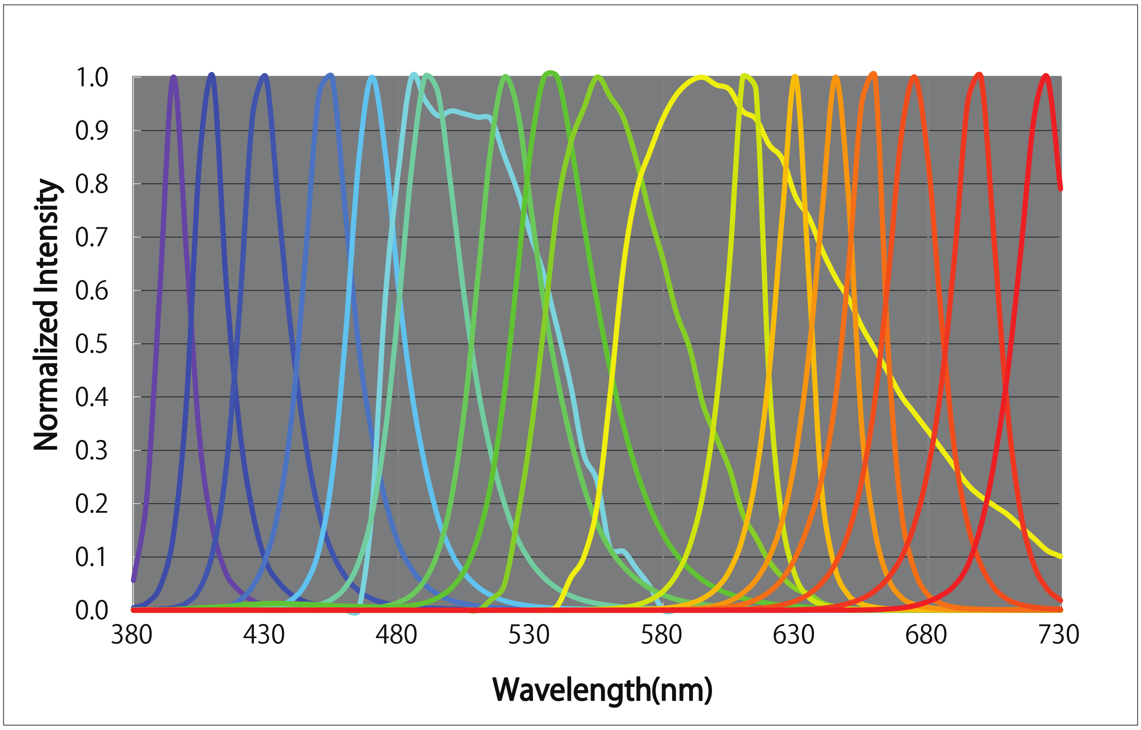


Figure 2 — Example of spectral power distributions for a chosen set of LEDs

4.2 Hardware requirements

4.2.1 General

This Clause is to describe a light emitting system for DSC colour characterization that uses an integrating sphere.

4.2.2 Operating condition

The light emitting system shall be designed to operate consistently under the following ranges.

NOTE "Temperature" condition was referred from ISO 12646.

- Temperature: 18 °C to 28 °C.
- Relative humidity: 15 % to 80 %.

4.2.3 Specifications of the system

4.2.3.1 Wavelength

The wavelength range over which the combined set of the light emissive devices is evaluated shall be 380 nm to 730 nm and should be 360 nm to 830 nm.

NOTE 1 The procedure to configure an LED array to achieve required spectral power distribution and chromaticity is described in Annex B.

NOTE 2 Evaluation metric (S_{R2L}) described in 4.2.3.2 can be applied to more extended range including IR/UV components when necessary.

4.2.3.2 Objective reference light source and calculated-reference light source

ISO 17321-1 describes that the spectral power distribution for illuminating the test target shall be photographic daylight, D55, as defined in ISO 7589. The standard illuminant D55 shall be used as a reference light source in this part of ISO 17321. A light source which is generated with a programmable light emission system is obtained by minimizing the S_{R2L} value in Formula (1). This optimization method is described in Annex B.

NOTE This programmable light emission system can generate other illuminants such as D65, A and so forth. D65 is used as the default illuminant for video uses.

4.2.3.2.1 Optimization procedure of a programmable light emission system to a reference light source

The mean of the squares of the differences between the objective reference and calculated light source spectral power distributions (S_{R2L}) is specified by:

$$S_{R2L} = \frac{\sum_{i=1}^{N} \left(\left(L_{ri} - P_S E_{ci} \right) / Y_N Y_V \right)^2}{N} \tag{1}$$

$$Y_N = \sum_{i=1}^{N} L_{ri} / N \tag{2}$$

$$Y_V = \sum_{i=1}^{N} V_{ri} L_{ri} / Y_N \tag{3}$$

$$\sum_{i=1}^{N} V_{ri} = 1 \tag{4}$$

where

L_{ri} is the reference light source spectrum of the *i*-th wavelength;

E_{ci} is the spectrum of the *i*-th wavelength calculated for the programmable light emission system;

P_S is the scaling coefficient to adjust energy power level;

Y_N is the normalization factor on averaged power of the objective reference light source;

Y_V is the factor to compensate light source dependence using luminosity factor in case of relative light source value;

V_{ri} is the normalized-response of the the *i*-th wavelength derived from the luminosity function;

N is number of wavelength samples ($i = 1, N$).

The optimization procedure is as follows.

a) Measure the (absolute) spectral power distribution of each LED at its maximum intensity. This shall be done in the same way with the same units used, for example watts/(Sr × m^2 × nm), for each LED.

b) Using the optimization procedure described in Annex B, minimize the S_{R2L} value. This procedure calculates an LED intensity coefficient b_j of measured spectrum intensity ε_{ij} for *j*-th LED. A value of P_s is determined as follows. When one of the LEDs will be driven at its maximum coefficient, P_s is set to be the maximum value of b_j ($j = 1, M$). P_s is specified as the scaling coefficient for generating D55 illuminant or arbitrary light sources.

    The following notations are used.

    N is number of wavelength samples ($i = 1, N$).

    M is number of LEDs.

    $\boldsymbol{b}$ is intensity vector having b_j component ($j = 1, M$).

    ε_{ij} is measured-spectral intensity of *j*-th LED ($j = 1, M, i = 1, N$).

c) Multiply each LED's measured spectral power distribution by the corresponding LED intensity coefficient b_j, and sum all of spectral power distributions to obtain E_{ci}.

d) Divide the summed spectral power distribution by P_s to obtain the calculated-spectral distribution E_{ci} of the programmable light emission system. E_{ci} is an output candidate spectrum distribution using the programmable light emission system.

$$E_{ci} = \sum_{j=1}^{M} b_j \varepsilon_{ij} \ / P_S \tag{5}$$

e) The calculated-reference light source spectrum distribution L'_{ri} corresponding to E_{ci} is obtained by dividing L_{ri} by P_S.

$$L'_{ri} = L_{ri} \ / P_S \tag{6}$$

L'_{ri} is used as the reference light source for optimization in 4.3.2 and 4.3.3.

The use of Y_V is optional. In cases where the luminosity function is applied independently (i.e. Y_V is not used), the value of Y_V should be set to 1,0.

NOTE 1 If normalization component L_{ri}/Y_N is not used, S_{R2L} values of illuminants with strong spectral peaks such as fluorescent lamps are smaller than those values of flat-like illuminants such as illuminant D55 and D65.

The maximum intensity of each light emitting device of the programmable light emission system can be determined beforehand from its hardware specification. It is recommended that these values are used as maximum constraint conditions for the optimization method described in Annex B in order to achieve the maximum intensity of each light emitting device. In this case, the intensity value is the maximum energy level of the corresponding light emitting device. In practice, the intensity values of light emitting devices should be set to lower levels than the maximum energy possible when reproducing spectra of objects colours. Intensity values for every light emitting devices for illuminant D55 can be determined using the optimization method with these constraint conditions.

NOTE 2 Exposure level and white balance setting for DSC can be achieved using light source power distribution above.

4.2.3.2.2 Evaluation for calculated light source

The evaluation for calculated light source of the programmable light emission system (S_{R2L}) is specified by Formula (1).

Annex F describes the calculation procedure of S_{R2L} if both relative spectral distribution of a reference light source and absolute spectral distribution of a measured light source are given.

4.2.3.3 Size, luminance, uniformity and angular characteristic

4.2.3.3.1 Output window

The output window (see Figure 1) shall be at least 50 mm in diameter.

4.2.3.3.2 Minimum luminance

The minimum luminance of the output window shall be greater than 40 cd/m^2 and should be greater than 80 cd/m^2 when simulating various light sources including fluorescent and LED light sources.

NOTE 80 cd/m^2 provides a luminance that allows an object illuminated by the source to be photographed satisfactorily at a distance of 50 cm using a DSC with an ISO speed of 200, an aperture of F5,6, a shutter speed of 1/30 s.

4.2.3.3.3 Uniformity

The luminance measured at the centre and at 8 points evenly spaced around the circumference of the output window at 45° intervals shall differ by no more than ±2 %. The luminance measurements are made normal to the plane of the output window at each measurement point.

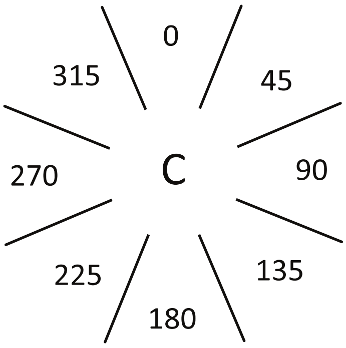


Figure 3 — Measurement points on the output window with every 45°

Figure 3 shows measurement points on the output window to calculate uniformity characteristics.

Uniformity is defined by the Formula (7):

$$\Delta Y_u = \frac{Y_k - Y_{\mathrm{ave}}}{Y_{\mathrm{ave}}} \times 100 \qquad (7)$$

where, Y_{ave} is the average luminance of Y_c and $Y_{k\mathrm{S}}$. Y_c is the luminance at the centre point and Y_k is luminance at the circumference point for k = 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°. ΔY shall be within ±2 %.

4.2.3.3.4 Angular characteristics

The luminance, when measured within a 10° cone angle to the normal line of the centre of the output window, shall differ by no more than ±2 %.

An integrating sphere, similar to that shown in Annex A, should be used in order to ensure uniformity across the output window. Figure 4 shows angular characteristic measurement method. It is the typical method for a colour target having an arrangement of an output window and light sources shown in Figure 1.

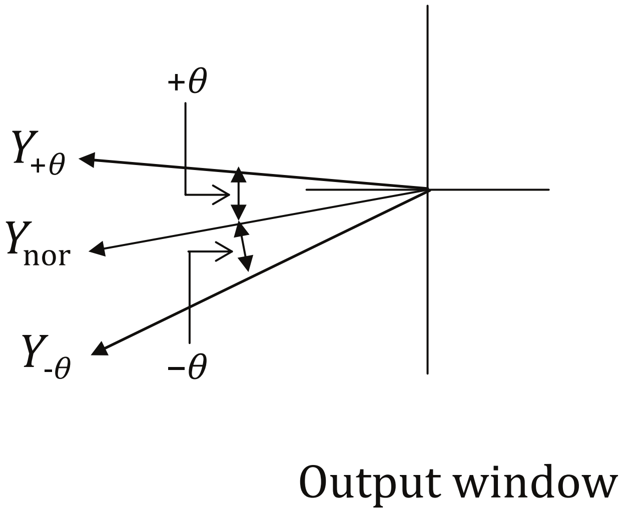


Figure 4 — Angular characteristics measurement method

$$\Delta Y_\theta = \frac{Y_{\pm\theta} - Y_{\mathrm{nor}}}{Y_{\mathrm{nor}}} \times 100 \qquad (8)$$

Where, Y_{nor} is luminance measured along the axis normal to the output window, $Y_{+\theta}$ or $Y_{-\theta}$ is luminance measured along the axis which is inclined $+\theta$ or $-\theta$ to the normal axis, respectively. Maximum θ is 5° of arc. ΔY shall be within ±2 %.

4.2.4 Time stability and long-term stability of light intensity

The following method shows how to calculate the time stability of light intensity.

Step 1: Generate CIE Illuminant D55 using the light emitting system.

Step 2: Allow the system to warm-up for an optimum time (e.g. 35 min) to reach stable state.

Step 3: Measure spectral power distribution every five minutes

Step 4: Repeat measurement of the spectral power distribution (step 3) at least seven times.

Step 5: Calculate ρ_{avi} as shown in Formula (9) and repeat for i = 1 to N to obtain averaged spectral power distribution ρ_{av}.

$$\rho_{avi} = \frac{\sum_{j=1}^{M} \left(\rho_{ij}\right)}{M} \tag{9}$$

where

ρ_{ij} is spectral intensity of i-th wavelength at j-th iteration (j = 1, M);

ρ_{avi} is time-averaged-spectral intensity of i-th wavelength;

ρ_{av} is spectral power distribution having ρ_{avi} components, where i = 1, N;

N is the number of wavelength samples (i = 1, N);

M is the number of the measurement iterations.

The wavelength range to be evaluated shall be 380 nm to 730 nm and should be 380 nm to 780 nm.

NOTE 1 M = 7 would be appropriate.

Step 6: Calculate tristimulus values $X_{av}Y_{av}Z_{av}$ of light source using ρ_{av} and CIE colour matching functions.

Step 7: Calculate tristimulus values $X_jY_jZ_j$ of light source using ρ_{ij} (i = 1, N) and CIE colour matching functions.

NOTE 2 $X_jY_jZ_j$ can be obtained by direct measurement with an appropriate instrument. $X_{av}Y_{av}Z_{av}$ are calculated by averaging operation of $X_jY_jZ_j$ (j = 1, M).

Step 8: Calculate $CIEDE2000_j$ using $X_{av}Y_{av}Z_{av}$ and $X_jY_jZ_j$.

NOTE 3 *CIEDE2000* is calculated under illuminant D55 condition.

Step 9: Calculate $CIEDE2000_{av}$, a time average of $CIEDE2000_j$, as shown in Formula (10):

$$CIEDE2000_{av} = \frac{\sum_{j=1}^{M} \left(CIEDE2000_j\right)}{M} \tag{10}$$

Step 10: Calculate standard deviation SD. This standard deviation means reproducibility of the light emitting system.

$$SD^2 = \frac{\sum_{j=1}^{M} \left(CIEDE2000_j - CIEDE2000_{av}\right)^2}{M} \tag{11}$$

Step 11: Calculate maximum $CIEDE2000_{max}$ of $CIEDE2000_j$

Figure 5 shows $X_jY_jZ_j$.

Requirements for reproducibility and maximum CIEDE2000 are described in Table 1.

NOTE 4 An optimum time to reach stability is 35 min in Figure 5.

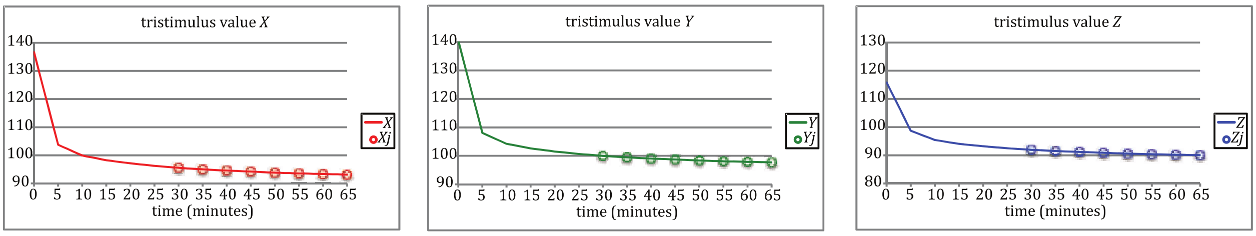


Figure 5 — $X_jY_jZ_j$ for measuring time stability of light source

Table 1 — Requirements for time stability of light intensity

	SHALL	SHOULD
Reproducibility (*SD*)	ΔE_{00} (CIEDE2000) ≤ 0,3	ΔE_{00} (CIEDE2000) ≤ 0,1
Maximum CIEDE2000	ΔE_{00} (CIEDE2000) ≤ 0,6	ΔE_{00} (CIEDE2000) ≤ 0,2

NOTE 5 The spectral power distribution of LEDs is very dependent on temperature and so it is very important that the temperature of LED array remains stable over time.

In order to determine the long-term stability, the tristimulus values of (X_j,Y_j,Z_j) of the light source shall be measured once a month following the warm-up period (e.g. 35 min) and recorded as described in 4.4.

Annex A shows one method to maintain stability over time using pulse width modulation in order to avoid spectral shift of LEDs with current change.

4.3 Figure of merit for a colour target using a programmable light emission system

4.3.1 General

A figure of merit for the programmable light emission system can be represented by the combination of two metrics: S_{R2} and CIEDE2000, described in this Clause. These two metrics shall always be indicated together as a combination, and shall not be used separately.

NOTE Annex C shows relationship between S_{R2} and CIEDE2000 colour difference.

4.3.2 Terms and notations of S_{R2}

The mean of the squares of the differences between two colour target spectral power distributions (S_{R2}) is specified by the following formulae:

$$S_{R2} = \frac{\sum_{i=1}^{N} [(\rho_{ri} - \rho_{ci}) / Y'_V]^2}{N} \tag{12}$$

$$Y'_V = \left(\sum_{i=1}^{N} V_{ri} L'_{ri}\right) / \left(\sum_{i=1}^{N} L'_{ri} / N\right) \tag{13}$$

where

L'_{ri} is the calculated reference light source spectrum of the i-th wavelength generated by the the programmable light emission system described in 4.2.3.2.1 e);

ρ_{ri} is the reference colour target spectrum of the i-th wavelength and its data range is 0-1. ρ_{ri} is corresponding to reflectance or transmittance;

ρ_{ci} is the spectrum of the i-th wavelength calculated for the programmable light emission system and its data range is 0-1. ρ_{ci} is corresponding to reflectance or transmittance. ρ_{ci} is obtained in Formula (15) described in 4.3.3.2;

Y'_V is the factor to compensate light source dependence using luminosity function in case of absolute light source value.

Data range of ρ_{ri} and ρ_{ci} is generally within 0,0 to 1,0, however, ρ_{ri} and ρ_{ci} can be over 1,0 in case of fluorescence emission simulation.

The use of Y'_V is optional. In cases where the luminosity function is applied independently (i.e. Y'_V is not used), the value of Y'_V should be set to 1,0.

Annex F describes the calculation procedure of S_{R2} if a relative reference light source spectral distribution and a measured-colour target spectral distribution are given.

NOTE 1 S_{R2} has same physical meaning of RMS (Root Mean Square) in Reference [18] if the factor to compensate light source dependence Y'_V is removed. The square of RMS is S_{R2}.

NOTE 2 If the factor to compensate light source dependence Y'_V is not used, S_{R2} values of illuminants with strong spectral peaks such as fluorescent lamps are smaller than those values of flat-like illuminants such as illuminant D55 and D65.

4.3.3 Method for the calculation of S_{R2}

4.3.3.1 Calculation steps

The following steps shall be used to calculate the metric S_{R2} between spectrum of the programmable light emission system and a reference spectrum.

4.3.3.2 Step A: Calculate closest matching spectrum

Reference colour spectral power distributions are determined by users and should include sets of colours that are important for their application area.

NOTE For general purpose colour imaging, the X-Rite Color Checker Classic, shown in Figure B.1, is recommended with illuminant D55 as the recommended illuminant.

To obtain the closest spectrum matching system with the reference spectrum, S_{R2} shown in Formula (12) should be minimized. This procedure calculates a coefficient b_j of measured spectrum intensity ε_{ij} for j-th LED using same procedure as 4.2.3.2.1 b). A coefficient b_j is 0-1 range value. An output candidate spectrum distribution E_{ci} for a colour target under the reference light source L'_{ri} using the programmable light emission system is shown in Formula (14). ρ_{ci} is obtained in Formula (15).

$$E_{ci} = \sum_{j=1}^{M} b_j \varepsilon_{ij} \qquad (14)$$

$$\rho_{ci} = \sum_{j=1}^{M} b_j \varepsilon_{ij} \; / L'_{ri} \qquad (15)$$

Calculate the closest matching spectrum using a nonlinear Generalized Reduced Gradient (GRG) algorithm (this is commonly available in software packages for scientific and engineering use). Details of this procedure are shown in Annex B.

Repeat for all spectral power distributions.

4.3.3.3 Step B: Calculate CIEDE2000 and S_{R2}

a) Calculate CIEDE2000 between spectrum of the reference spectrum and spectrum of corresponding spectrum distribution of the programmable light emission system for all reference colour spectra under the illuminant D55. The reference light source is used as white condition of CIEDE2000 calculation.

b) Calculate S_{R2} between the reference spectrum and the corresponding spectrum distribution of the programmable light emission system for all reference colour spectra.

4.3.4 Figure of merit

Figures of merit of the programmable light emission system shall be the following:

- average value and maximum value of S_{R2};
- average value and maximum value of CIEDE2000.

S_{R2} is correlated with the number of light emitting devices if light emitting devices are well selected. Annex B shows the selection method for light emitting devices.

Annex E shows figures of merit for colorimetric image capturing using high-end DSC.

CIEDE2000 is very dependent on bit depth for intensity of the light emitting devices, and so, greater than 10-bit modulation should be used when intensity of the light emitting device is linear.

S_{R2} is the primary metric and CIEDE2000 is a supplementary metric.

For DSC colour characterization, the use of the data set of the spectrum generated by the programmable light emission system as measured on that occasion is recommended, in order to avoid effects of calculation errors and time dependent shifts of the system characteristics.

4.4 Report

Reporting form for hardware is described in Table 2 and for spectral distribution in Table 3.

Figure 6 shows long-term stability of tristimulus values.

Table 2 — Reporting form for hardware requirements

Classification	Content	Frequency
Date of measurement	yyyy.mm.dd	Every time
Operating condition Temperature	Temperature : xx,x °C Relative humidity : xx,x %	Every time
Luminance	xx,x cd/m^2	Every day
Uniformity	ΔY_u :± x,x %	Once a month
Angular characteristics	ΔY_θ :± x,x %	Once a month
Time stability of light intensity	Reproducibility (*SD*) : ΔE_{00} (CIEDE2000) ≤ x,x Maximum CIEDE2000 : ΔE_{00} (CIEDE2000) ≤ x,x	Once a month
Long-term stability of light intensity	Tristimulus values X_j,Y_j,Z_j,	Once a month

Table 3 — Reporting form for spectral distribution

Colour target use	
Reference light source	D55 (for example) If no standard illuminant is used, a reference light source spectra need to be described in other table.
Measured data or calculated data	Measured data (for example)
Wavelength	Reflectance 0-1 range data
380 nm	0,xxxx
Every 5 nm or 10 nm (user definable) interval	
730 nm	0,xxxx
Evaluation metrics	
Y_V used or not	Not (Example)
S_{R2}	0,00xx
CIEDE2000	x,xx

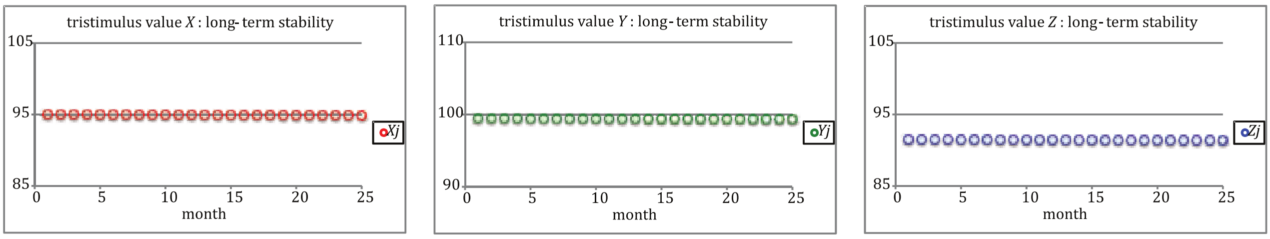


Figure 6 — Long-term stability of tristimulus values

Annex A
(informative)

Integrating sphere method and LED-driving method

A.1 Integrating sphere method

Figure A.1 shows a typical integrating sphere which emits bluish green light. The diameter of the integrating sphere should be five times greater than the diameter of the output window of the integrating sphere.

Figure A.1 — Sample of integrating sphere emitting bluish green light

A.2 LED-driving method

Figure A.2 shows an LED driving signal/method.

LEDs emit light only in periods of on-time *Tpi* which are indicated by upper levels of driving wave forms in the figure. However, the perceived light intensity of the LEDs is proportional to time averaged values of pulse wave forms for a short cycle time *Tfi*. This phenomenon is valid for not only still-cameras, but also video cameras which have a rather long exposure time. Therefore, we adopt the method for controlling LED light intensity by changing a pulse width *Tpi*, and/or a cycle time *Tfi*.

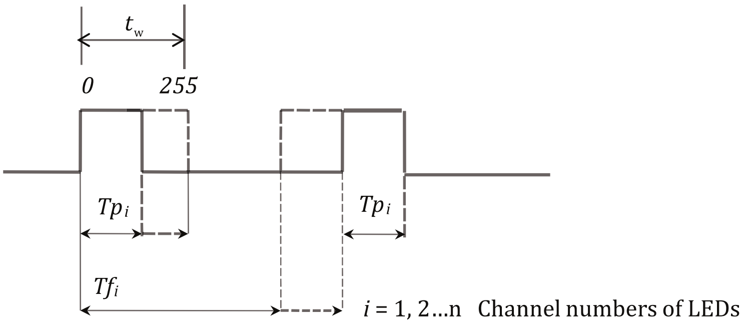
In the circuit, an LED is driven in two states, on and off. The LED current is maximum and constant in on-state: a higher level and zero in off-state: a lower level. The time averaged light intensity of the LED is proportional to time averaged values of on-time.

Tpi is the duration of on-time of "*i*" LED, and ranged from 0, a minimum value, to t_W which is maximum on-time corresponding to 255 digital value in 8-bits system. "*i*" is a number of LEDs. Every LED has its own independent drive circuitry and is driven by constant current at on-time.

Tfi is a cycle time of the circuits, which is changed from t_W to 10 ms. Cycle time of 10 ms is set as maximum cycle time in order to avoid flickering effects on cameras and spectral colorimeters. The time condition is also good for a person when he sees the colour target directly without seeing flicker.

Every LED intensity, *Tfi* and *Tpi*, is determined under the conditions so that the colour target can emit enough intensity for testing cameras.

Figure A.3 shows a block scheme of LED colour target drive circuit. Each LED has its own drive circuit.



Tp_i : On - time of an LED

$0 < Tpi < t_w$

t_w : Maximum of on - time

Tf_i : Cycle - time.

$t_w < Tfi < 10$ ms

Figure A.2 — LED control signal time dependencies for one channel

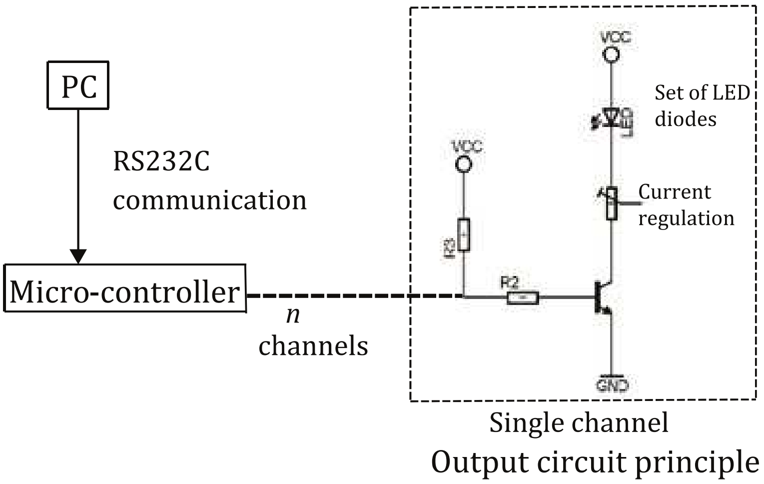


Figure A.3 — LED colour target driving circuit block diagram

Annex B

(informative)

Spectral power distribution optimization procedure for multiple LEDs

B.1 General

This Annex provides one method that can be used to select an initial set of LEDs and a method to select an optimal subset by removing LEDs in turn such that the remaining set of LEDs is the subset that best matches a set of reference spectra.

The spectral range to be analysed is 380 nm to 730 nm with a sampling interval of 5 nm.

A set of reference colour reflection targets that include a set of colours to be simulated by the LED programmable light emission system is selected.

These reference colour targets are determined by users and should include sets that are important for their application area. For general purpose colour imaging, the X-Rite Color Checker Classic, shown in Figure B.1, is recommended. Spectral reflectance data for X-Rite Color Checker Classic are described in ISO 17321-1:2012, Annex C.

CIE Illuminant D55 is used as the light source to illuminate these reference colour targets.

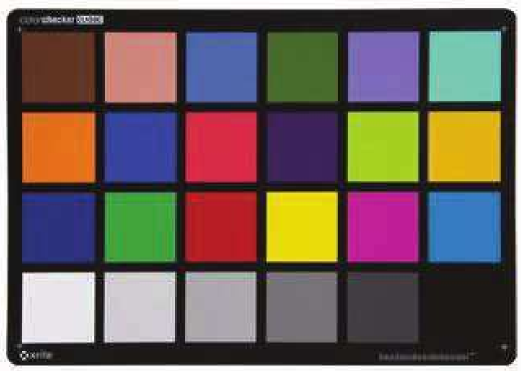


Figure B.1 — X-Rite Color Checker Classic

B.2 Step 1: An example of LED

A set of LEDs (in this case 18) is selected. An example of such an LED set is shown in Figure B.2.

NOTE The number of LEDs to be used is selected by the programmable light emission system designer.

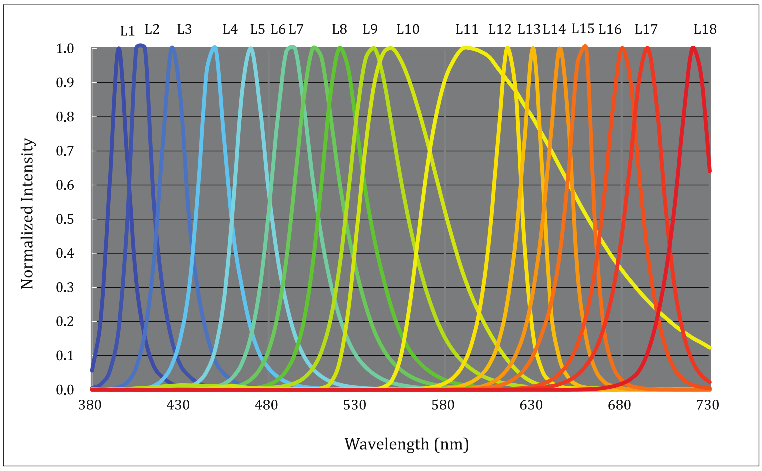


Figure B.2 — Spectral power distribution of a set of LEDs (example)

B.3 Step 2: Determination of initial values of LEDs intensities

The candidate set of LEDs selected at step 1 is analysed to determine their ability to match a number of reference colour spectra by minimizing the sum of the squares of the differences between the closest matching spectrum achievable by the candidate LED set and the reference colour spectrum.

This is done by adjusting the relative intensity of each LED in the candidate set to achieve the best spectral match for each standard colour spectrum. In this case, the best spectral match is the match with the smallest value for the sum of the square of the difference.

The best spectral match is done by LSQ (Least Square method) as described below.

NOTE This LSQ procedure is described except P_S, Y_N and Y_V in Formula (1) for easy understanding. Almost the same procedure is applied to Formula (12) for colour target uses. This Annex uses relative intensity spectra instead of measured absolute intensity spectra for each LED.

The following notations are used.

N : number of wavelength samples (i = 1, N).

M : number of LED

$\boldsymbol{b}$: intensity vector having b_j component (j = 1, M)

b_j : intensity of j-th LED (j = 1, M)

ε_{ij} is the component of j-th LED (i = 1, N, j = 1, M)

$\boldsymbol{y}$: aimed spectrum vector having y_i component (i = 1, N)

Matrix D has ε_{ij} component, and its row and column are N and M.

D^T : transposed matrix of D

The vector, ***b***, is obtained using Formula (B.1):

$$\boldsymbol{b}=(D^T D)^{-1} D^T \boldsymbol{y} \tag{B.1}$$

The calculated spectrum $\boldsymbol{y}'$ is calculated using Formula (B.2):

$$\boldsymbol{y}' = D \ \boldsymbol{b} \tag{B.2}$$

If vector, ***b***, has no negative value, $\boldsymbol{y}'$ is optimal spectrum to obtain minimum S_{R2} value.

The following stepwise LSQ procedure can give optimal solution for intensities of LEDs to obtain minimum S_{R2} value.

a) Let N be the number of LEDs.

b) Calculate a vector, ***b***, using Formula (B.1). If there are no negative values in ***b***, ***b*** is the optimal solution to obtain minimum S_{R2} value and no further steps are necessary.

c) If there is a negative value in ***b***, remove the corresponding LED and re-calculate ***b*** vector for (N-1) LEDs using Formula (B.1). This value for ***b*** is the optimal solution.

d) If there are multiple negative values, let M be the number of negative values. For all of combinations $_NC_{M-1}=N!/[(N-M+1)!(M-1)!]$ check whether there is a combination where no negative intensity exists.

a) If there is a combination with no negative intensity, this is the optimal solution.

b) If there is no combination with no negative intensity, remove all M LEDs and go to step (a) with $N'=N-M$.

Though this stepwise LSQ procedure can produce the optimal solution, it is very complicated and time-consuming. Other methods may also be used.

Initial values of LEDs intensities for a nonlinear algorithm are obtained using a vector "***b***" of LSQ method.

B.4 Step 3: Optimization using nonlinear generalized reduced gradient (GRG) algorithm

A nonlinear GRG algorithm is used in order to minimize the sum of the squares of the differences between the closest matching spectrum achievable by the candidate LED set and the target colour spectrum.

The result of the nonlinear algorithm is very dependent on the initial input values of LEDs intensities. One method to improve the result is to use a vector "***b***" of LSQ method described in step 2. There is no need to set negative values to zero because nonlinear GRG algorithm is constrained so that no negative intensity is produced.

In cases where the S_{R2} value is satisfactory but the CIEDE2000 value is not satisfactory, some constraint on colour chromaticity is added to the nonlinear GRG algorithm for optimization. This process will improve the better CIEDE2000 value but makes the S_{R2} value slightly worse.

NOTE The constraint conditions on colour chromaticity is CIEDE2000.

To optimize for spiky spectral power distribution, S_{R2} may have a larger value. It is useful to provide some constraint condition on colour chromaticity for this case.

It is recommended to select the best combination of S_{R2} and CIEDE2000.

B.5 Step 4: Reduction method of number of LEDs

The use of more LEDs is likely to produce better S_{R2} values and CIEDE2000 values, however, more LEDs force more cost and more footprint to install many LEDs. So, the programmable light emission system designers have to consider a better balance among better quality, reasonable cost, footprint and so forth. This subclause describes how to reduce number of LEDs.

The nonlinear GRG algorithm is used with the initial values as described in B.3 in order to minimize the sum of the squares of the differences between the closest matching spectrum achievable by the candidate LED set and the target colour spectrum.

The aim of this step is to reduce the number of LEDs and for each step the LED that has the least influence on the ability of the set of LEDs to match the set of reference colour is identified and removed from the set. The way in which this is done is to “turn off” a single LED from the set in turn and to score the effectiveness of the remaining LEDs. In this way, one LED is removed from the set in each iteration. If necessary, this process can be repeated multiple times.

The following describes each step.

a) Select one of the M LEDs and set its intensity to zero. M is number of LEDs.

b) For each of the reference patches, adjust the remaining (M-1) LED intensities to minimize the sum of the squares of the difference between the LED target spectrum and the reference spectrum and record this minimum error value.

c) Take the average of these minimum values for all of the reference patches. This value is recorded as the figure of merit for the (M-1) LED set. Repeat steps a) to c) for all M LEDs.

d) Identify the (M-1) LED set with the lowest figure of merit and use this set. If necessary, repeat steps a) to d) with this new set of LEDs to further reduce the number of LEDs to (M-2).

Steps a) to d) above can be repeated as many times as is necessary to reduce the number of LEDs to the desired number.

Annex C
(informative)

The need for constraints on the average values and maximum values of S_{R2} and CIEDE2000

This Annex describes the relationship between S_{R2} and CIEDE2000 for the 17 LEDs set and the need for constraints on the average values and maximum values of S_{R2} and CIEDE2000. There are 18 combinations using 17 LEDs if one LED from the 18 LED set described in Figure B.2 is removed.

a) Calculate S_{R2} and CIEDE2000 metrics for 24 colour patches in the X-Rite Color Checker Classic for each of these 18 combinations under illuminant D55.

b) Calculate the average and maximum values of S_{R2} and CIEDE2000 for the following:

- all patches M1 - M24;
- mid-saturated patches M1 - M12;
- high-saturation patches M13 - M18;
- grey patches M19 – M24

for each combination of LEDs.

Figure C.1 shows the relationship between the S_{R2} average and the CIEDE2000 average for 18 combinations using 17 LEDs.

Figure C.2 shows the relationship between the S_{R2} maximum and the CIEDE2000 maximum for 18 combinations of 17 LEDs.

There are many cases where some combinations have a better S_{R2} average value and a worse CIEDE2000 average value, and some combination have a better S_{R2} maximum value and a worse CIEDE2000 maximum value. It is, therefore, necessary to add some constraint conditions for the S_{R2} average value, the CIEDE2000 average value, the S_{R2} maximum value and the CIEDE2000 maximum value.

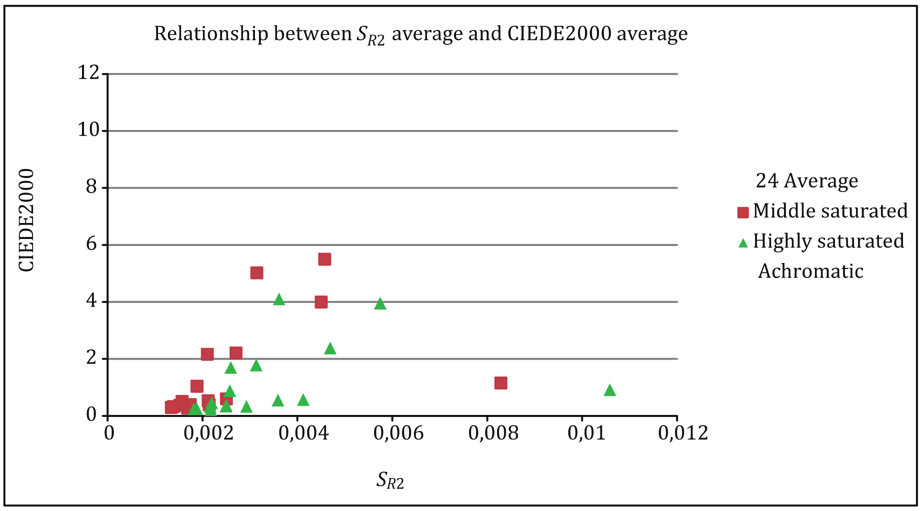


Figure C.1 — Relation between S_{R2} average and CIEDE2000 average for 18 combinations using 17 LEDs set

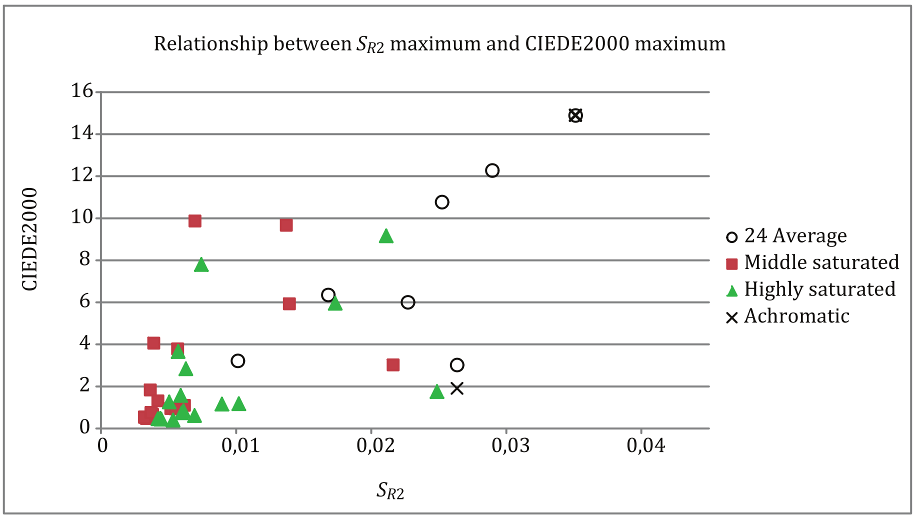


Figure C.2 — Relation between S_{R2} maximum and CIEDE2000 maximum for 18 combinations using 17 LEDs set

Annex D
(informative)

Evaluation method for light source generated by a programmable light emission system

D.1 General

This system may also be used to create a light source. Where the intended use of the light source is visual colour comparison, the colour rendering index may be used to evaluate the light source simulation. Where the intended use of the light source is for DSC evaluation or purposes other than visual comparison, the metric S_{R2L} and Colour Rendering Index might be used to evaluate the quality of the light source simulation.

D.2 S_{R2L} metric

The mean of the squares of the differences between the relative spectral power distributions of two light sources (S_{R2L}) is specified in 4.2.3.2.2. This S_{R2L} is used as an evaluation metric for light sources.

D.3 Colour rendering index

It is recommended that the General Colour Rendering Index, *Ra* as defined in CIE 13.3, is greater than or equal to 98.

It is recommended that the Special Colour Rendering Index, *Ri* as defined in CIE 13.3, is greater than or equal to 95.

NOTE 380 nm to 780 nm to be evaluated in CIE 13.3 is specified. 380 nm to 730 nm is used in this part of ISO 17321.

D.4 CCT [T_{cp}] and Duv metrics

The correlated colour temperature CCT [T_{cp}] is specified by CIE pub 17-258 and Duv is specified by ANSI C78.377-2008. These metrics are very useful to evaluate light sources.

T_{cp} is the temperature of the Plankian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a diagram, where the (CIE 1931 standard observer based) u′, 2/3v′ coordinates of the Plankian locus and the test stimulus are depicted.

Duv is the closest distance from the Plankian locus on the (u′, 2/3v′) diagram, with + sign for above and – sign for below the Plankian locus.

D.5 Examples

Table D.1 shows a comparison between a number of evaluation metrics such as S_{R2L}, several colour rendering indexes, chromaticity coordinates (x,y), CCT [T_{cp}] and D_{uv} of spectral power distributions calculated by the LED programmable light emission system set up to match CIE standard illuminants D65, D55 and A. The wavelength range is 380 nm to 730 nm and the wavelength step is 5 nm.

Table D.1 — Evaluation metrics for light sources

Target number (Munsell HV/C)	D65	D65	D65	D55	D55	A	A
	Light box	18 LEDs	14 LEDs	18 LEDs	14 LEDs	18 LEDs	14 LEDs
S_{R2L}	0,015 6	0,011 4	0,015 0	0,008 7	0,010 8	0,016 8	0,035 4
1(7,5R6/4)	96,4	99,3	98,1	99,1	96,5	98,4	93,8
2(5Y6/4)	96,6	99,7	99,3	99,6	98,7	99,4	97,9
3(5GY6/8)	97,3	99,8	98,8	99,6	97,9	98,9	94,6
4(2,5G6/6)	97,4	99,5	98,4	99,3	96,8	98,6	94,2
5(10BG6/4)	96,9	99,5	98,6	99,4	97,3	98,8	95,3
6(5PB6/8)	95,2	99,7	99,2	99,7	98,8	99,7	98,9
7(2,5P6/8)	97,5	99,7	98,1	99,6	97,7	99,2	94,8
8(10P6/8)	98,1	99,3	95,4	99,0	94,9	98,2	88,6
9(4,5R4/13)	95,6	97,5	86,6	97,1	86,8	96,2	76,6
10(5Y8/10)	92,3	99,5	98,7	99,4	98,0	99,5	98,0
11(4,5G5/8)	95,3	99,6	98,6	99,6	97,1	99,1	95,2
12(3PB3/11)	94,3	98,3	99,4	98,2	98,9	96,6	96,2
13(5YR8/4)	95,5	99,4	98,5	99,2	97,1	98,5	94,5
14(5GY4/4)	98,4	99,8	99,3	99,7	98,6	99,2	96,5
Ra=R1-8	96,9	99,5	98,2	93,4	97,3	98,9	94,8
R9-14	95,2	99,0	96,8	98,9	96,1	98,2	92,8
R1-14	96,2	99,3	97,6	99,2	96,8	98,6	93,9
Chromatic coordinates (x, y)	(0,315 9, 0,481 5)	(0,313 5, 0,481 2)	(0,314 5, 0,482 1)	(0,333 2, 0,523 0)	(0,333 0, 0,523 3)	(0,448 2, 0,739 8)	(0,449 7, 0,741 7)
CCT [T_{cp}] Unit : K	6 331,1	6 451,9	6 398,4	5 469,5	5 479,6	2 850,6	2 827,9
Duv	0,001 8	0,003 5	0,003 1	0,003 5	0,003 8	0,000 2	0,000 0

Figure D.1 shows spectral power distributions of D65, a Light box D65 simulator and two spectral power distributions calculated by the LED programmable light emission system.

Figure D.2 shows spectral power distributions of D55 and two spectral power distributions calculated by the LED programmable light emission system.

Figure D.3 shows spectral power distributions of Illuminant A and two spectral power distributions calculated by the LED programmable light emission system.

The sets of LEDs used in Table D.1, and Figure D.1, D.2 and D.3 are as follows:

- an 18 LED set (L1, L2, L3, L4, L5, L6, L7, L8, L9, L10, L11, L12, L13, L14, L15, L16, L17 and L18) with spectra as shown in Figure B.1;
- a 14 LED set (L1, L2, L3, L4, L5, L6, L8, L10, L11, L13, L15, L16, L17 and L18) with spectra as shown in Figure B.1.

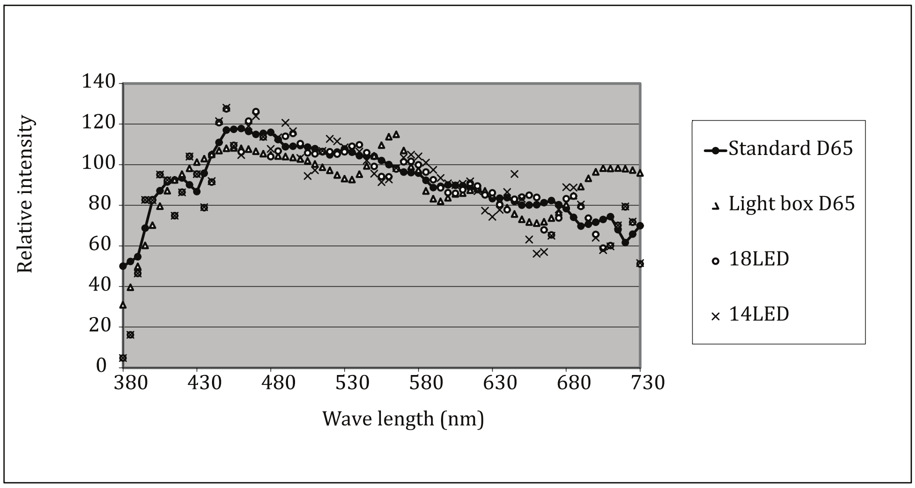


Figure D.1 — Spectral power distributions of D65 and Light box D65 compared with two spectral power distributions calculated by the LED programmable light emission system

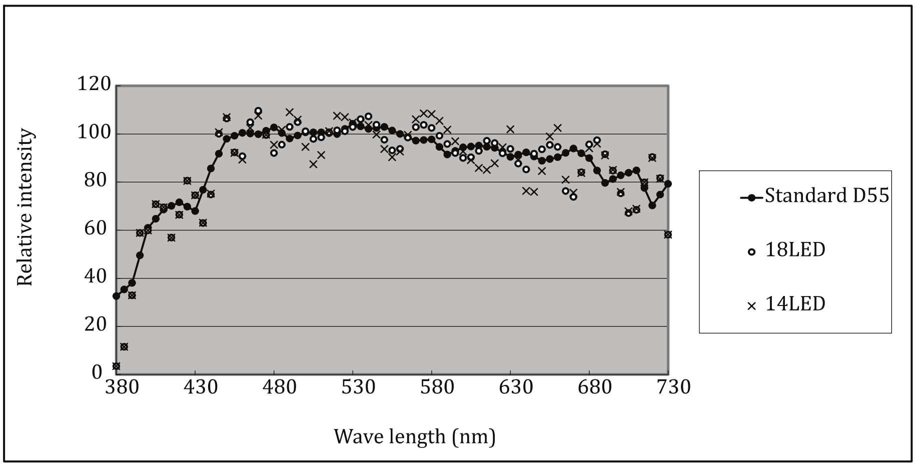


Figure D.2 — Spectral power distributions of D55 compared with two spectral power distributions calculated by the LED programmable light emission system

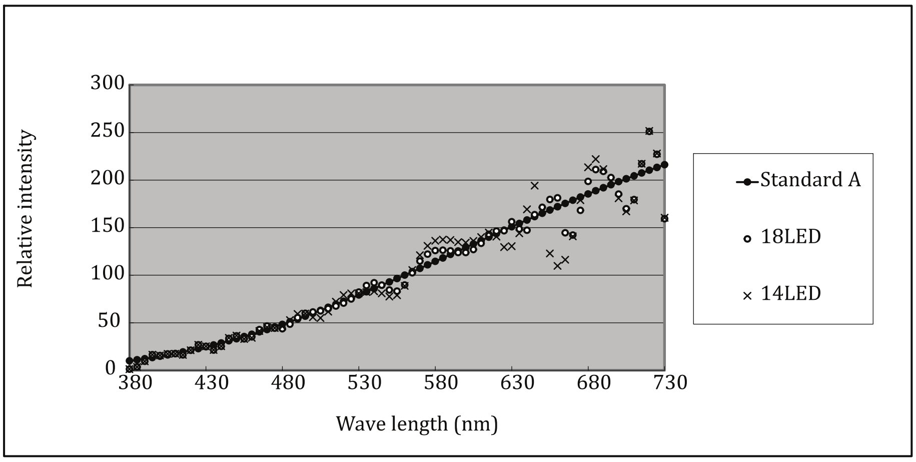


Figure D.3 — Spectral power distributions of Illuminant A compared with two spectral power distributions calculated by the LED programmable light emission system

Annex E
(informative)

S_{R2} and CIEDE2000 recommendations for colorimetric image capture

E.1 General

There are fields where accurate colour reproduction is essential, such as colour inspection of industrial products such as the colours of automobile bodies, cosmetics, clothes and those of telemedicine and digital archives. In these fields, it is often required that the average colour difference between colours of a captured image and an object is less than one CIEDE2000. In digital printing, it is generally known that the colour discrimination threshold between two printed images is around two CIEDE2000.

In order to achieve the accuracy, it is recommended that a programmable light emission system used for colour calibration of DSCs for colorimetric image capture has figure of merits of S_{R2} and CIEDE2000 as described in Table E.1.

E.2 Calculation of S_{R2}

The following steps are used to calculate the metric S_{R2} between a calculated spectrum by the programmable light emission system and a reference spectrum.

E.3 Step A: Calculate closest matching spectrum

Reference colour spectral power distributions are determined by users and should include sets of colours that are important for their application area. For general purpose colour imaging, the X-Rite Color Checker Classic reference chart is recommended. Spectral reflectance data for the X-Rite Color Checker Classic reference chart are described in ISO 17321-1:2012, Annex C.

Illuminant D55 is used as the light source to illuminate these reference colour targets.

Calculate the closest matching spectrum using the nonlinear GRG as a general nonlinear optimization method as shown in Annex B.

NOTE There is no need to perform CIEDE2000 optimization.

Repeat for all spectral power distributions.

E.4 Step B: Calculate CIEDE2000 and S_{R2}

a) Calculate CIEDE2000 between spectrum of the reference spectrum and spectrum of corresponding LED-generated spectrum distribution for all reference colour spectra.

b) Calculate S_{R2} between spectrum of the reference spectrum and spectrum of corresponding LED-generated spectrum for all reference colour spectra.

E.5 Requirement for S_{R2} and CIEDE2000

Figures of merit of the programmable light emission system are the following:

- average value and maximum value of S_{R2};

— average value and maximum value of CIEDE2000.

Recommendations for the sum of the squares of the differences (S_{R2}) between the closest matching spectrum achievable by the candidate LED set and the target colour spectrum and CIEDE2000 between two spectra are described in Table E.1. 24 colours of X-Rite Color Checker Classic are used here.

Requirements of S_{R2} and CIEDE2000 are based on ideal conditions which mean there is no hardware error.

An average value may not be useful here and a maximum value is only important for highly saturated colours which do not exist in reflective colour targets.

NOTE S_{R2} is the primary metric and CIEDE2000 is a supplementary metric.

Table E.1 — Recommendations of S_{R2} and CIEDE2000

S_{R2}	Average value for colour targets	≤0,001 8
	Maximum value for colour targets	≤0,007 2
CIEDE2000	Average value for colour targets	≤0,50
	Maximum value for colour targets	≤1,50

Annex F
(normative)

S_{R2L} and S_{R2} calculation methods for a light emission system in which spectral distribution is only obtained by measurements

F.1 General

It is possible to calculate S_{R2L} and S_{R2} for measured spectral distribution data if objective reference light source data and reference reflectance data are given. F.2 shows a calculation procedure for evaluation for a light source. F.3 shows a calculation procedure for figure of merit for a colour target.

F.2 Evaluation for a light source case

It is possible to calculate S_{R2L} if relative spectral distribution of a reference light source spectral distribution L_{ri} and spectral distribution of a measured-light source E_{mi} are given.

The evaluation metric S_{R2L} for light source is given by Formula (F.1). P_{M1} is obtained by differentiating Formula (F.1) with P_{M1}.

$$S_{R2L} = \frac{\sum_{i=1}^{N} \left((L_{ri} - P_{M1} E_{mi}) / Y_N Y_V \right)^2}{N} \tag{F.1}$$

$$Y_N = \sum_{i=1}^{N} L_{ri} / N \tag{F.2}$$

$$Y_V = \sum_{i=1}^{N} V_{ri} L_{ri} / Y_N \tag{F.3}$$

$$P_{M1} = \sum_{i=1}^{N} (L_{ri} E_{mi}) / \sum_{i=1}^{N} (E_{mi} E_{mi}) \tag{F.4}$$

where

E_{mi} is the measured spectrum of the i-th wavelength generated by the programmable light emission system;

P_{M1} is the scaling coefficient to adjust energy power level, given in Formula (F.4).

The use of Y_V is optional. In cases where the luminosity function is applied independently (i.e. Y_V is not used), the value of Y_V should be set to 1,0.

F.3 Figure of merit of S_{R2} for a colour target of which spectral data is obtained only by measurements

It is possible to calculate S_{R2} if a relative reference light source spectral distribution L_{ri}, reflectance distribution of reference colour target ρ_{ri} (0 to 1 range data) and a measured-colour target spectral distribution E_{mi} are given.

The evaluation metric S_{R2} for a colour target is given by Formula (F.5). The estimated-reflectance of colour target is given by Formula (F.6) and the absolute spectral distribution La_{ri} of reference light source is given by Formula (F.8). P_{M2} is obtained by differentiating Formula (F.5) with P_{M2}.

$$S_{R2} = \frac{\sum_{i=1}^{N} \left|(\rho_{ri} - \rho_{mi}) / Y_V\right|^2}{N} \tag{F.5}$$

$$\rho_{mi} = P_{M2} E_{mi} / L_{ri} \tag{F.6}$$

$$P_{M2} = \sum_{i=1}^{N} (\rho_{ri} E_{mi} / L_{ri}) / \sum_{i=1}^{N} (E_{mi} E_{mi} / L_{ri} L_{ri}) \tag{F.7}$$

$$La_{ri} = \sum_{i=1}^{N} L_{ri} / P_{M2} \tag{F.8}$$

where

ρ_{mi} is the estimated-spectrum of the i-th wavelength generated by the light emission system;

P_{M2} is the scaling coefficient to adjust energy power level, given in Formula (F.7).

It is possible to calculate CIEDE2000 using La_{ri}, ρ_{ri} and ρ_{mi}.

The use of Y_V is optional. In cases where the luminosity function is applied independently (i.e. Y_V is not used), the value of Y_V should be set to1,0.

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