19NRM02 “RevStdLED”

Guideline

on required minimum specifications and detailed work procedures

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Content

1 Introduction

The basic idea of this document is to provide detailed work procedures for test laboratories to implement correlations in measurement uncertainties when determining photometric quantities like luminous responsivity, illuminance and luminous flux based on spectral measurements. As the determination of uncertainty is mainly a software task, the work procedures are strongly connected to software code which is freely available in the GitHub repository of the 19NRM02 RevStdLED project. As a matter of fact, there are a huge variety of software products available on the market (like Mathcad©, Mathematica©, Origin©, etc.) which can be used to calculate the uncertainty of measurements including correlations. However, to allow even small test laboratories to develop and implement their own software tools to allow for the dissemination of GUM conform uncertainty estimations, it was decided to use the open source language Python as the basis for the guidelines of this Project.

2 General

From the economic point of view, the quality of the measurement equipment to be installed for a measurement process shall always depend on the overall uncertainty that must be achieved by the measurement method in the laboratory. The requirements in the guideline "A2.2.1 Guideline on Measurement setup" provide a first indication on the equipment sufficient to achieve uncertainties of photometric quantities in the range of 1 %. If higher uncertainties are permitted, the requirements could be possibly reduced. However, a 5 ½ Digit Voltmeter does not guarantee per se measurement uncertainties in parts of 10^{-4}. In addition to the ability of the instrument itself, the boundary conditions of the measurement process must also allow for such low uncertainties. If there is a noisy signal or some leakage current, the voltage reading can be much more uncertain than expected. Therefore, the uncertainty of the instrument is always the lower limit of the possible uncertainty contribution.

3 Luminous responsivity based on spectral measurements

The purpose of this work procedure is to assist testing laboratories to implement correlations in measurement uncertainties when determining the luminous responsivity of photometers traceable to spectral responsivity measurements.

Starting point for further considerations in this guideline is a radiometer, calibrated according to spectral responsivity and provided with a covariance matrix showing the correlation of the measurements at different wavelengths. These radiometers are used to determine the spectral responsivity of photometers, which is necessary to calculate their luminous responsivity and allows spectral mismatch corrections.

3.1 *Description of procedures*

The spectral luminous responsivity of a photometer head is obtained by the substitution method using a reference detector and a spectrally tuneable quasi monochromatic light source (mostly realized by a suitable light source and a monochromator). Depending on the required uncertainty level, a radiometer based on a single silicon photodiode detector or on a Si trap detector calibrated according to spectral irradiance typically serves as a reference detector.

Both detectors, the photometer head and the reference radiometer (e.g. the. Si photodiode) have to be compared under identical geometric conditions, i.e. in the same direction and distance from the source (e.g. monochromator output) to their effective entrance aperture. It also has to be ensured, that the entrance apertures of both detectors are spectrally and spatially uniform and symmetrically illuminated. This is especially critical if both detectors do not have the same size of aperture. The measurement signal of the photometer head or the calibrated reference detector to the applied monochromatic irradiance is measured directly as photocurrent, or if a transimpedance amplifier is used, as a voltage, in which case it must be divided by the feedback resistor used. By using the measured values and the certified absolute responsivity values of the reference detector, the spectral irradiance responsivity values of the photometer head are obtained according to:

$$s_{\mathrm{Ph}}(\lambda) = \frac{J_{\mathrm{Ph}}(\lambda)}{J_{\mathrm{Ref}}(\lambda)} \cdot s_{\mathrm{Ref}}(\lambda) \tag{1}$$

The spectral irradiance responsivity can be used to determine the absolute luminous responsivity, which refers to standard Illuminant A:

$$s_{\mathrm{v}} = \frac{s_0}{K_{\mathrm{m}}} \frac{\int_{\lambda_1}^{\lambda_2} S_{\mathrm{A}}(\lambda) \cdot s_{\mathrm{Ph,\,rel}}(\lambda) \cdot \mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} S_{\mathrm{A}}(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda} \tag{2}$$

with

$$s_{\mathrm{Ph}}(\lambda) = s_0 \cdot s_{\mathrm{Ph,\,rel}}(\lambda) \tag{3}$$

$s_{\mathrm{Ph}}(\lambda)$:	spectral irradiance responsivity of the photometer head, unit; [$\mathrm{A \cdot m^2 \cdot W^{-1}}$]
$J_{\mathrm{Ph}}(\lambda)$:	measured photocurrent of the photometer head output at a certain wavelength, unit; [nA]
$J_{\mathrm{Ref}}(\lambda)$:	measured photocurrent of the reference detector at a certain wavelength, unit; [nA]
$s_{\mathrm{Ref}}(\lambda)$:	certificated spectral responsivity values of the reference detector, unit; [$\mathrm{A \cdot m^2 \cdot W^{-1}}$]

s_0: wavelength independent normalization factor for the relative spectral responsivity of the photometer head, unit; [$A \cdot m^2 \cdot W^{-1}$]

s_V: absolute photometric responsivity of the photometer head, unit; [$A \cdot lx^{-1}$]

$S_A(\lambda)$: relative spectral distribution of the light source emitting Illuminant A, unit; [-]

$V(\lambda)$: spectral luminous efficiency function for photopic vision, unit; [-]

$s_{V(\lambda),\mathrm{rel}}(\lambda)$: relative spectral responsivity values of the photometer, unit; [-]

K_m: maximum spectral luminous efficacy for photopic vision, unit; [683 $lm \cdot W^{-1}$]

3.2 Description of artefacts

The device object of the calibration is an illuminance meter. Therefore the spectral responsivity of the device is similar to the visual efficacy function V(λ). The illuminance meter shall include a V(λ) corrected detector connected to an electronic device that can display the current delivered by the detector.

3.3 Criteria for acceptance/rejection of artefacts

In order to perform the spectral responsivity measurement the device should allow to have access to the current delivered by the detector. The detector must be of stable construction, i.e.there must be no loose parts inside the detector.

3.4 Parameters and quantities to be determined

The quantity to be determined is the luminous responsivity that requires the following quantities or parameters to be measured:

- The spectral responsivity of the DUT on the spectral range 360 nm- 830 nm
- The current delivered by the DUT and the reference detector
- The spectral distribution of the of the light source

3.5 Required references

A list of measurement equipment used as references shall be kept, including:

- Calibrated reference detector with known spectral responsivity
- Calibrated ammeter or a calibrated voltmeter associated to a calibrated current/voltage amplifier to measure the current delivered by DUT and reference detector
- Calibrated monochromator in wavelength
- Calibrated ruler for distance measurements
- Temperature gauge

3.6 Devices and equipment including technical requirements

3.6.1 Measurement set-up

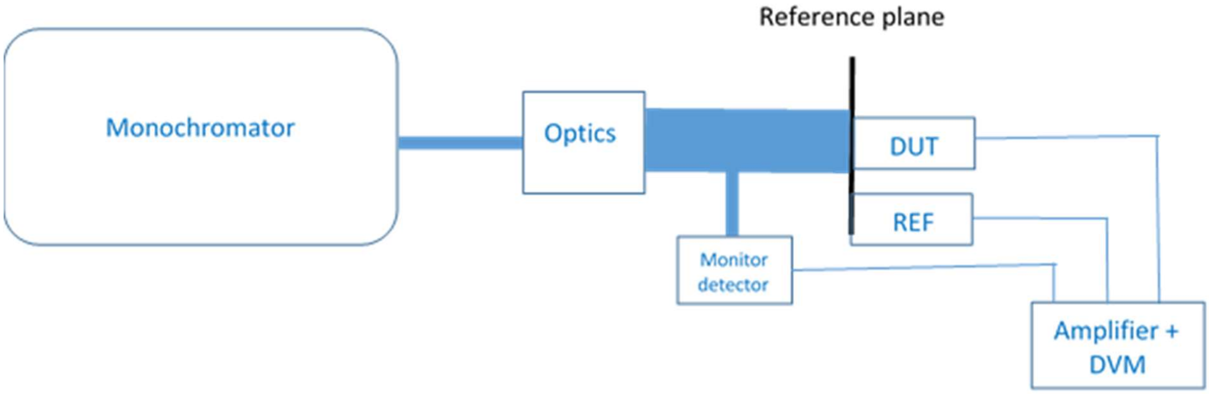

Figure 1General setup for the determination of the spectral responsivity of Detectors

Taking the model of evaluation given in Equation (2) into account, the minimum requirements for an appropriate measurement setup according to Figure 1 for such spectral measurements are:

1. stable monochromatic light source: In most cases the light from a tungsten halogen lamp for the visible spectral range (e.g. 1000W FEL type lamp) is focused onto the entrance slit of a double monochromator operating in subtractive mode which provides the most uniform spectral irradiance behind the exit slit of the monochromator. The spectral bandpass should not exceed 5 nm in the spectral range of interest. A 1 nm bandpass would be ideal. The double monochromator shall provide a symmetrical triangular bandpass. The output radiation of the monochromator should be collimated to provide a uniform and high irradiance spectral radiation field which needs to overfill the detector entrance windows to be measured.
2. stable current source for the monochromator lamp (e.g. Output: 10A/140V in case of a 1000 W FEL type lamp) with an output drift of less than $1 \cdot 10^{-4}\ \mathrm{h}^{-1}$.
3. a series of spectral line sources (e.g. pen-ray light sources) that can be installed sequentially on the optical axis of the monochromator to calibrate the wavelength scale of the monochromator system in the required range from 360 nm to 830 nm (but at least 380 nm to 780 nm).
4. a set of solid-state lasers (e.g. red, green and blue laser pointers) to check the symmetry of the slit function and Bandwidth at least at some point of the spectral range of the monochromator (this can also be provided by the manufacturer of the monochromator system).
5. xyz-stage to align the detectors to be compared in front of the collimator, such that the effective entrance aperture of the reference detector and the photometer are mounted at the same distance, centric and perpendicular to the optical axis of monochromator.

6. temperature controller for the reference detector and the photometer in order to be able to set the temperature of the detectors specified in the calibration certificates.
7. temperature sensor to monitor the ambient temperature of the measurement setup
8. two calibrated nanoammeter (or one with two input channels) for the reference detector and the photometer (or tow voltmeters in combination with a transimpedance amplifier connected to the detectors) with sufficient resolution (e.g. 5 1/2 digits) to measure the detector outputs.
9. voltmeter in combination with transimpedance amplifiers connected to the monitor detector
10. a distance meter or measuring probe to accomplish correct setting of the measurement distance of the entrance window of photomter and reference detector.

Information about the (spectral) uniformity of the photometer head can be determined separately by a relative measurement in which the entrance window of the detector is scanned with a light beam e.g. from the set of solid-state lasers used for the bandwidth and slit-function measurement. Also, the spectral dependency on temperature can be characterized in a separate measurement by changing the detector's temperature by $\pm 5\ °\mathrm{C}$ at certain wavelength settings.

3.6.2 Software

To allow for the propagation of correlation a Monte Carlo Method is used to calculate the expected values and the uncertainty of the requested quantities. The Monte Carlo Method uses the model of evaluation where the input variables of this model are randomly varied according to their probability distributions. If two input variables are correlated, a modified probability distribution is used based on the marginal distributions and the correlation matrix of the correlated quantities.

3.7 Data to be documented

Beside the calibrated luminous responsivity and its combined uncertainty, the illuminance used as well as the type of source and the spectral range used for the calculation shall be documented. In addition, the temperature condition must be reported.
If the spectral distribution of the integral value of the spectral responsivity is requested, the spectral data including the covariance matrix or the correlation matrix is required.

3.8 Measurement procedure

Measurement of the spectral responsivity of the photometer is performed according to the following steps:

- Switch-on the light source and set the proper supplied current.
- Switch-on all electronic devices and let them warm-up for at least 1 hour before taking measurements.
- Mount the photometer head on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup.
- Mount the reference detector on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup.
- If using a monitor detector check that this detector is properly placed to detect the light from the source independent from the photometer head and reference detector to account for source drifts during the whole measurement process.

The measurement method is a substitution method, and the following steps are performed:

- Set the wavelength of the monochromatic beam λ_i with a spectral bandwidth of 5 nm or less.
- Move the photometer into the light beam. Measure (average of 30 readings):
  - The current $J_{SPh}(\lambda_i)$ of the photometer with the light on and the signal $U_{Mon.Ph}(\lambda_i)$ of the monitor detector.
  - The dark current $J_{DPh}(\lambda_i)$ of the photometer when the beam is switched of using an appropriate shutter.
  - Determine the signal of the photometer $J_{Ph}(\lambda_i)$ as

$$J_{Ph}(\lambda_i) = J_{SPh}(\lambda_i) - J_{DPh}(\lambda_i) \tag{4}$$

- Move the reference detector into the light beam. Measure (average of 30 readings):
  - The current $J_{Sref}(\lambda_i)$ of the reference detector with the light on and the signal $U_{Mon.Ref}(\lambda_i)$ of the monitor detector.
  - The dark current $J_{Dref}(\lambda_i)$ of the reference detector when the beam is switched of using an appropriate shutter.
  - Determine the signal of the reference detector $J_{Ref}(\lambda_i)$ as

$$J_{Ref}(\lambda_i) = J_{SRef}(\lambda_i) - J_{DRef}(\lambda_i) \tag{5}$$

Repeat the measurements for all wavelengths within the spectral range of 360 nm to 830nm if possible (or at least between 380 nm to 780 nm) with at least a wavelength step of 5 nm or less.

3.9 Uncertainty evaluation

3.9.1 Model of evaluation for spectral data

Although the simple physical model in equation (1) leads one to assume a simple model of evaluation the spectral correlations of the integral quantities visible in the correction terms of equation (6) must be explicitly treated for the model of evaluation of equation (2). In addition, spectral measurements with monochromators usually take longer, so a monitor detector may be required, located in one arm of the monochromator output beam split for this purpose, to compensate for possible drifts of the setup. To reduce the possible drift of the spectral irradiance, a fairly stable monochromator source (e.g. a pre-aged tungsten halogen lamp) shall be used for the visible range. In addition, the measurement sequence should be such that the reference detector and the photometer head are compared at every single wavelength and not after a complete wavelength sweep. In this way, also the alignment uncertainty for reference detector and photometer due to repeatability in positioning is reduced in the calculation of integral quantities due to averaging, while it would otherwise result in a systematic offset for all spectral measurements. However, if chromatic aberration occurs (due to lenses of prisms used), realignment may be necessary in between.

For the most general case, the reference detector is calibrated according to spectral power, and the model of evaluation will be:

$$s_{\mathrm{Ph}}(\lambda) = \frac{J_{\mathrm{Ph}}(\lambda) \cdot U_{\mathrm{Mon,Ref}}}{J_{\mathrm{Ref}}(\lambda) \cdot U_{\mathrm{Mon,Ph}}} \cdot s_{\Phi,\mathrm{Ref}} \cdot (\lambda) \cdot A_{\mathrm{Ref}} \cdot c_{wl}(\lambda) \cdot c_{bw}(\lambda) \cdot c_{pol}(\lambda) \cdot c_{unif}(\lambda) \cdot c_{T,\mathrm{Ref}}(\lambda) \cdot c_{T,\mathrm{Ph}}(\lambda) \cdot c_{dist} \tag{6}$$

where

$s_{\mathrm{Ph}}(\lambda)$: spectral irradiance responsivity of the photometer head, unit: [A·m²·W^{-1}]

$J_{\mathrm{Ph}}(\lambda)$: measured photocurrent of the photometer head at a certain wavelength; Student T-distribution based on the mean and the standard distribution of the repeated measurements with the number of readings represented by the degrees of freedom of the distribution, unit: [nA]

$J_{\mathrm{Ref}}(\lambda)$: measured photocurrent of the reference detector at a certain wavelength; Student-T-distribution based on the mean and the standard distribution of the repeated measurements with the number of readings represented by the degrees of freedom of the distribution, unit: [nA]

$U_{\mathrm{Mon,Ref}}$: simultaneous reading of the monitor detector (here: voltage at the output of a transimpedance amplifier connected to the monitor detector) when the reference detector is measured. Student-T-distribution based on the mean and the standard distribution of the repeated measurements with the number of readings represented by the degrees of freedom of the distribution; unit: [V]

$U_{\mathrm{Mon,Ph}}$: simultaneous reading of the monitor detector (here: voltage at the output of a transimpedance amplifier connected to the monitor detector) when the photometer is measured. Student-T-distribution based on the mean and the standard distribution of the repeated measurements with the number of readings represented by the degrees of freedom of the distribution; unit: [V]

$s_{\Phi,\mathrm{Ref}\cdot}(\lambda)$: spectral power responsivity of the reference detector from calibration certificate; Ideally provided with a correlation matrix of dimension N with $\lambda_1 \le \lambda \le \lambda_N$ so that the spectral responsivity can be treated as a correlated N-dimensional multivariate quantity within the Monte Carlo simulation. Normally it would be stated in the calibration certificate that the single $s_{\mathrm{Ref}}(\lambda)$ values will follow a Gaussian distribution, unit: [nA·W^{-1}]

A_{Ref}: effective area of the entrance window of the reference detector; Gaussian distributed as stated in the calibration certificate; unit: [m²]

$c_{wl}(\lambda)$: spectral correction factor for the wavelength calibration, Gaussian distributed, unit: [-]

$c_{bw}(\lambda)$: spectral correction factor for bandwidth effects; Gaussian distributed, unit: [-]

$c_{\mathrm{unif}}(\lambda)$: spectral correction factor for the nonuniformity of the detector and reference and its impact with respect to nonuniform radiation caused by the monochromator; Gaussian distributed, unit: [-]

$c_{T,\mathrm{Ref}}(\lambda)$: spectral correction factor for the temperature dependency of the reference detector; Uniform distributed, unit: [-]

$c_{T,\mathrm{Ph}}(\lambda)$: spectral correction factor for the Temperature dependency of the photometer; Uniform distributed, unit: [-]

c_{dist}: correction for distance offset between photometer head and reference detector; Uniform distributed, unit: [-]

3.9.2 Model of evaluation for photometric data

Equation (6) allows to determine the uncertainty of the spectral responsivity data of the photometer. The uncertainty of the luminous responsivity measurement must take the measurement model given in equation (2) into account (4) and by introducing correlation between the spectral data arising from the uncertainty of the measurement of the wavelength. Equation (2) can be written as:

$$s_{\mathrm{v}} = \frac{s_0}{K_{\mathrm{m}}} \frac{\sum_{\lambda_1}^{\lambda_2} S_{\mathrm{A}}(\lambda_i) \cdot s_{\mathrm{Ph,\,rel}}(\lambda_i) \cdot \Delta\lambda}{\int_{\lambda_1}^{\lambda_2} S_{\mathrm{A}}(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda} \tag{7}$$

The spectral data in the sum are characterised over the spectral range by their correlation over the wavelength. If no details about the correlation is known, the correlation with respect to the neighbouring wavelength points can be estimated according to CIE 198 SP2 (CIE, 2018) if the variance associated to $S_{Ph.rel}(\lambda_i)$ is approximated by:

$$u^2\left(S_{Ph.rel}(\lambda_i)\right) = \left(\frac{\partial S_{Ph.rel}}{\partial \lambda}(\lambda_i)\right)^2 \ u^2(\lambda) \tag{8}$$

Then the estimated covariance associated with $S_{Ph.rel}(\lambda_i)$ and $S_{Ph.rel}(\lambda_j)$ is given by:

$$u\left(S_{Ph.rel}(\lambda_i), S_{Ph.rel}(\lambda_j)\right) = \frac{\partial S_{Ph.rel}}{\partial \lambda}(\lambda_i)\frac{\partial S_{Ph.rel}}{\partial \lambda}(\lambda_j)\, u^2(\lambda) \tag{9}$$

3.9.3 Implementation of Monte Carlo Method

At every single wavelength, the readings of the photometer current and the monitor detector value during the photometer head measurement as well as the reading of the reference detector current and the monitor detector value during the reference measurement are correlated and need to be treated after setting up the respective correlation matrices.

So far, the number of N determined individual values of $s_{\mathrm{Ph}}(\lambda)$ are single spectral values that are strongly correlated via the measurement itself as well as via the values of $s_{\Phi,\mathrm{Ref.}}(\lambda)$, which must be taken into account when calculating s_{v} according to Equations 6 and 7.

4 Luminous intensity and chromaticity coordinates based on spectral measurements

This work procedure is meant for calibration of LED lamps, single LEDs or LED based luminaires or modules (abbr. LED). It can in principle also be used for filtered filament lamps provided that the filtered lamps are stable and reproduceable.

4.1 Description of procedures

4.1.1 Luminous intensity

Based on a calibrated photometer with known luminous responsivity s_v (see 3) and known relative spectral responsivity and a calibrated spectroradiometer to determine the relative or absolute spectral irradiance the LED source of which the luminous intensity has to be determined, the luminous intensity is measured at a known distance where the photometric distance law is valid. Whether the distance law is valid or not, this is checked by distance variation, showing that the illuminance is strictly following the square-law. To allow for distance variation without changing geometry an optical bench system is used, on which the LED, the photometer and the spectroradiometer input optic are aligned on a common optical axis, using proper alignment tools. For the sake of simplicity, we assume in this chapter that the spectroradiometer is an array spectroradiometer, which supplies count values as output values.

When using a photometer, the luminous intensity is obtained provided by:

$$I_\mathrm{v} = \frac{d^2}{\Omega_0} \cdot \frac{J_\mathrm{Ph}}{s_\mathrm{v}} \cdot F \qquad (10)$$

with the mismatch correction factor F given by:

$$F = \frac{\int_{\lambda_1}^{\lambda_2} S_\mathrm{A}(\lambda) s_\mathrm{rel}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_\mathrm{A}(\lambda)\, V(\lambda) d\lambda} \frac{\int_{\lambda_1}^{\lambda_2} S(\lambda) V(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, s_\mathrm{rel}(\lambda) d\lambda} \qquad (11)$$

where

s_v:	luminous responsivity of the calibrated photometer head, unit; [A·lux^{-1}]
J_Ph:	measured photocurrent of the calibrated photometer head, unit; [nA]
d:	measurement distance, unit; [m]
Ω_0:	unit of steradian, [sr]
$s_\mathrm{rel}(\lambda)$:	certificated relative spectral responsivity values of the photometer, unit; [A·m^2·W^{-1}]
$S(\lambda)$:	relative spectral distribution of the light source under test, unit; [nm^{-1}]
$S_\mathrm{A}(\lambda)$:	relative spectral distribution of the light source emitting Illuminant A, unit; [nm^{-1}]
$V(\lambda)$:	spectral luminous efficiency function for photopic vision, unit; [-]
λ_1, λ_2:	lower and upper wavelength limit (380nm to 780nm, or 360nm to 830nm)

Especially if LED sources are measured, it might be favourable to request a photometer calibration according to e.g. LED Illuminant L41 as a reference instead of Illuminant A. In this case, the calibration certificate should also provide the calibration source weighted relative responsivity $s^*_\mathrm{rel,C}(\lambda)$, with correlation information.

$$s^*_\mathrm{rel,C}(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} S_\mathrm{C}(\lambda) V(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_\mathrm{C}(\lambda)\, s_\mathrm{rel}(\lambda) d\lambda} s_\mathrm{rel}(\lambda) \qquad (12)$$

This would reduce the effort in the determination of the mismatch correction factor, which now reduces to:

$$F = \frac{\int_{\lambda_1}^{\lambda_2} S(\lambda) V(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, s^*_\mathrm{rel,C}(\lambda) d\lambda} \qquad (13)$$

where

$S_\mathrm{C}(\lambda)$: relative spectral distribution of the calibration light source emitting e.g. illuminant L41, unit; [nm^{-1}]

The relative spectral irradiance of the DUT is measured wavelength by wavelength (scanning monochromator system) or in one step over the entire spectral range (array spectroradiometer), where a dark measurement is used in between to account for drift and external straylight. In case of a scanning monochromator the use of a monitor detector checking the stability of the source is strongly recommended. Baffles are used wherever necessary to reduce straylight originating from the DUT.

In case of using directly a calibrated (array-)spectroradiometer instead of a photometer, equation (10) simplifies to:

$$I_\mathrm{v} = \frac{d^2}{\Omega_0} \cdot K_\mathrm{m} \int_{\lambda_1}^{\lambda_2} y_s(\lambda) \cdot \frac{1}{s_\mathrm{spec}(\lambda)} \cdot V(\lambda) d\lambda \qquad (14)$$

with

$y_s(\lambda)$: measured spectral irradiance signal of the spectroradiometer, unit [counts]

$s_\mathrm{spec}(\lambda)$: sensitivity of spectroradiometer, i.e. the spectral calibration factor for spectral irradiance, unit [count m² nm W^{-1}]

where the spectral distribution $S(\lambda)$ of the Light source is given by:

$$S(\lambda) = \frac{y_s(\lambda)}{s_\mathrm{spec}(\lambda)} \qquad (15)$$

After measuring the spectral irradiance data, the integral luminous intensity value is determined by mathematical weighting of individual spectral data with the $V(\lambda)$ Function. As the spectral data measurements and the calibration data is typically partly correlated, respective calculations regarding this correlation must be applied (see 3.9.2 and GPG on calculation of integral quantities using correlated data). If the spectral distribution of the calibration source differs from that of the test item, influences of stray light and bandpass must also be taken into account.

4.1.2 Chromaticity coordinates

The chromaticity coordinates (x, y) of a light source with the spectral distribution $S(\lambda)$ in the CIE 1931 xy chromaticity diagramm, are derived from its Tristimulus values X, Y, Z:

$$x = \frac{X}{X+Y+Z}\ ,\ y = \frac{Y}{X+Y+Z}\ ,\ z = \frac{Z}{X+Y+Z} = 1 - x - y \qquad (16)$$

where

$$X = \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot \bar{x}(\lambda) \mathrm{d}\lambda \ , \qquad Y = \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot \bar{y}(\lambda) \mathrm{d}\lambda \, , \qquad Z = \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot \bar{z}(\lambda) \mathrm{d}\lambda \qquad (17)$$

with

$\bar{x}(\lambda)$: red colour matching function of the CIE standard colorimetric observer

$\bar{y}(\lambda)$: green colour matching function of the CIE standard colorimetric observer, $\bar{y}(\lambda) = V(\lambda)$

$\bar{z}(\lambda)$: blue colour matching function of the CIE standard colorimetric observer

The procedure to deterrmine X, Y, Z in equation (17) is in principle the same as with the luminous intensity of equation (14), except that only the relative values of the integrals are needed. In case of the use of a Tristimulus Head, i.e. a colour head containing a photometer with three channels for red, green and blue, the procedure used for equation (10) must be followed. As the result of equation (16), the chromaticity coordinates x and y are physically correlated due to the overlap of the chromaticity functions. Therefore, the colour coordinate is a so-called multivariate quantity. And hence, the resulting two-dimensional correlation matrix must also be taken into account. And, as a result, the typical expansion factor k for a confidence interval of 95 %, which is about $k = 2$ for univariate quantities is increased to $k = 2{,}45$ (see 4.8.2.2).

4.2 Description of artefacts

The objects of calibration are LED based Lamps, luminaires or modules, where also single LEDs may be considered as an LED lamp. They may be operated directly with DC current or by a built-in power supply, which is operated with AC voltage. The size and form of the LED lamp must fit properly into the holders of the setup, allowing all adjustments necessary to measure the quantities required. The maximum size of the artefact also depends on the maximum achievable distance between source and spectroradiometer. As the luminous intensity as well as the chromaticity coordinates are directional quantities, the origin of the source point to be measured (e.g. the optical centre) and the direction of measurement with respect to a reference surface of the device must be defined prior measurement.

4.3 Criteria for acceptance/rejection of artefacts

The LED lamp must show a stable and reproducible behaviour, so that it can be expected that the values measured will be valid also at the customer's site if the boundary conditions that were valid during the calibration are reproduced. The lamps must comply with the boundary condition specified in Section 4.2

4.4 Parameters and quantities to be determined

Beside the integral and spectral data which are measured by the photometer and the spectroradiometer in the spectral range from typically 360 nm to 830 nm, or at least from 380 nm up to 780 nm, the LED lamp current and voltage and the LED lamp temperature shall be measured and documented. Especially if the LED lamp is passively cooled, its orientation during the measurement must be reported. Also, direction and distance of the measurement shall be documented.

4.5 Required references

A list of measurement equipment used as references shall be kept, including:

- Calibrated ruler for distance measurements
- Calibrated photometer including its relative spectral responsivity.
- Calibrated spectroradiometer or array spectroradiometer:
    - amplitude calibrated against a spectral irradiance standard or calibrated against a spectrally calibrated LED Lamp with spectral distribution comparable to DUT.
    - wavelength calibrated using e.g. a set of Pen-Ray lamps to provide known line spectra for wavelength calibration of the spectroradiometer.
- Calibrated voltmeter to measure lamp voltage.
- Calibrated amperemeter or a calibrated voltmeter and a calibrated shunt resistance to measure lamp current.
- Temperature gauge

Ideally, the correlation matrix or covariance matrix should be available for all distributions.

4.6 Device and equipment including technical requirements

4.6.1 Measurement setup

The Measurement setup should be located in a straylight reduced environment (preferably a room painted black, or separation of the measurement setup by black velvet curtains). The room should be temperature stabilized to fulfil the requirements of CIE S 025.

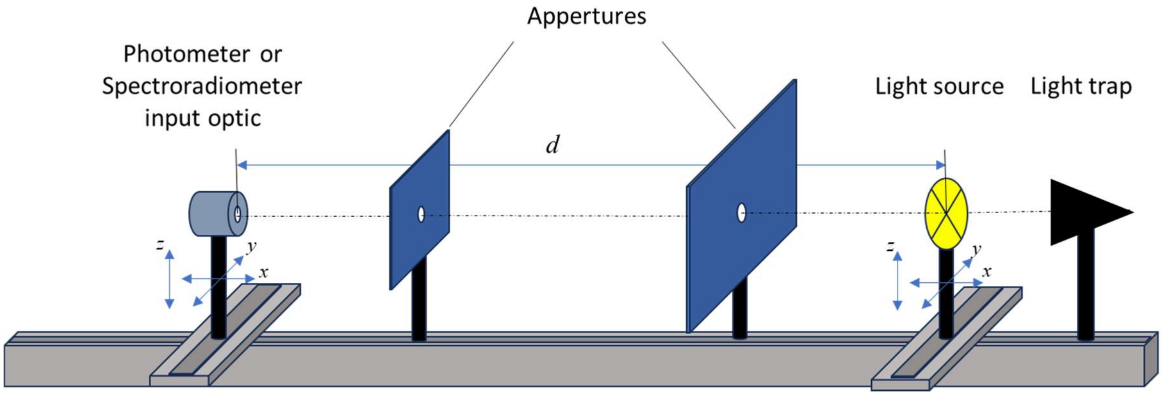

Figure 2 Optical bench setup to perform luminous intensity measurements

1. Luminous intensity measurements are usually performed using an optical bench system (see Figure 2) to align the source to be measured and the required detectors in a suitable and reproducible manner so that the entrance window of the detector and the desired measurement plane of the source are aligned parallel to each other and their centres lie on the same optical axis at a distance that satisfies compliance with the photometric distance law. The minimum requirement for the setup is a kind of optical bench system with a set of baffles to reduce straylight and two xyz-stages to mount and align the sources and detectors used.
2. In case of direct measurement using an (array-)spectroradiometer:
   a. Calibration light source for the amplitude calibration of the spectroradiometer: In most cases a tungsten halogen lamp for the visible spectral range (e.g. 1000W FEL type lamp) is used and placed in the required calibration distance in front of the spectroradiometer to be calibrated.
   b. stable current source for the calibration lamp (e.g. Output: 10A/140V in case of a 1000 W FEL type lamp) with an output drift of less than $1 \cdot 10^{-4}\ \mathrm{h}^{-1}$.
   c. a series of spectral line sources (e.g. pen-ray light sources) that can be installed sequentially on the optical axis of the spectroradiometer to calibrate the wavelength scale of the spectroradiometer in the required range from 360 nm to 830 nm (but at least 380 nm to 780 nm).
3. In case of measurement using a calibrated photometer:
   a. Calibrated photometer with known relative spectral responsivity distribution
   b. a calibrated nanoammeter for the reference photometer (or a voltmeters in combination with a transimpedance amplifier connected to the photometer) with sufficient resolution (e.g. 5 1/2 digits) to measure the photometers outputs.
   c. temperature controller for the reference photometer in order to be able to set the temperature of the detector specified in the calibration certificates.

4. stable current or voltage source for the DUT (type of source depends on the DUT to be measured) with an output drift of less than $1 \cdot 10^{-4}\ \mathrm{h}^{-1}$.
5. temperature sensor to monitor the ambient temperature of the measurement setup.
6. a distance meter or measuring probe to accomplish correct setting of the measurement distance of the entrance window of photomter and reference detector.

4.6.2 Software

To allow for the propagation of correlation a Monte Carlo Method is used to calculate the expected values and the combined uncertainty of the requested quantities. The Monte Carlo Method uses the model of evaluation where the input variables of this model are randomly varied according to their probability distributions. If two input variables are correlated, a modified probability distribution is used based on the marginal distributions and the correlation matrix of the correlated quantities.

4.6.2.1 Luminous intensity

Additional information and examples are provided in (19NRM02, 2023)

4.6.2.2 Chromaticity coordinates

Additional information and examples are provided in (19NRM02, 2023)

4.7 Data to be documented

4.7.1 Luminous intensity

Besides the calibrated luminous intensity and its combined expanded uncertainty the nominal current and voltage of the LED source as well as its operating temperature shall be documented if the data can be made available. In addition, the spectral range used for the determination of the integral photometric value must be reported.
If the spectral distribution of the integral value is requested, the spectral data including the covariance matrix or the correlation coefficient matrix should be provided.

4.7.2 Chromaticity coordinates

For the tristimulus values the same requirements as for the luminous intensity is valid, as X,Y,and Z behave as the luminous intensity. However, the chromaticity values are a multivariate quantity and hence, the two-dimensional covariance matrix for the chromaticity value has also to be reported and, regarding the expanded uncertainty, it has to be taken into account that its value is increased due to the increased expansion factor (see 4.1.2).

4.8 Measurement procedure

4.8.1 Measurement

4.8.1.1 Luminous intensity

Measurement of the luminous intensity of an LED source can be done using various procedures. Here, the absolute measurement using a calibrated photometer and using a spectroradiometer are explained. However, it would also be possible to compare the LED-source to be measured with a known LED-source of the same type. In this case, the spectral mismatch correction can be omitted and there is also no need for absolute calibration of the photometer or spectroradiometer. Using the procedures mentioned above, the measurement is performed according to the following steps:

- Switch-on all electronic devices and let them warm-up for at least 1 hour before taking measurements.
- Switch-on the light source and set the proper supplied current or voltage.
- Mount the calibrated photometer head and the spectroradiometer input optic on the XYZ stage and adjust it's position with respect to the optical axis of the measurement setup.
- Mount a spectral line source (e.g. a pen-ray lamp) on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup.
- Measure the line spectra of the line source after the source and the instrument warmed up and repeat this procedure with a few other line sources that provide further spectral lines, so that finally the entire spectral range of interest (at least 380 nm to 780 nm) is covered.
- Determine the Wavelength scale of your spectroradiometer and its uncertainty.
- For spectroradiometer based traceable determination of the luminous intensity:
    - Mount the calibrated reference source on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup according to the calibration sheet.
    - Measure the absolute spectral distribution of the lamp at the given operating condition after the source and the instrument warmed up taking care about Dark signal, linearity, stray light, gain, wavelength uncertainty.
    - Determine the absolute calibration function of the spectroradiometer including correlation or covariance matrix using information about wavelength dependent Dark signal, straylight, linearity, gain and wavelength uncertainty.
- For determination of spectral mismatch (the following steps can be omitted, if the spectral distribution of the light source to be measured is known by other means).
    - Mount a source with known spectral distribution on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup.

  - Measure the spectral distribution of the lamp at the given operating condition after the source and the instrument warmed up taking dark signal, linearity and straylight into account.

  - Determine the calibration factor of the spectroradiometer to measure the relative spectral distributions of lamps (see absolute calibration, but constant factors can be omitted).

- Mount the (LED) light source to be measured on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup and at a distance required to obtain radiant or luminous intensity. (This should be checked by changing the distance to ensure that the measured signal follows the square law).

- Measure the required spectral data of the lamp at the given operating condition after the source and the instrument warmed up taking dark signal, linearity and straylight and gain where appropriate into account.

- For spectroradiometer based traceable determination of the luminous intensity:

  - Determine the absolute spectral radiance of the (LED) source and calculate the luminous intensity by using the distance and weighting the integral with $V(\lambda)$.

- For photometer-based determination of the luminous intensity:

  - Mount the calibrated photometer on the XYZ stage and adjust its position with respect to the optical axis of the measurement setup (ensure that the distance is still ok) .

  - Measure the absolute illuminance with the photometer.

  - Determine the luminous intensity using the distance, the calibration data of the photometer and the calculated spectral mismatch.

Repeat the measurements at each step to allow the determination of the standard deviation of the measurement and thus the determination of the respective contribution of the uncertainty component as part of the combined uncertainty analysis.

4.8.1.2 Chromaticity coordinates

Repeat the same steps as given in 4.8.1.1 for the other tristimulus functions $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$ in addition to of $V(\lambda) = \bar{y}(\lambda)$.

- Determine the chromaticity coordinates taking the correlation between the tristimulus functions into account.

4.8.2 Uncertainty evaluation

4.8.2.1 Luminous responsivity

4.8.2.1.1 Model of evaluation for spectral data

For the most general case, the array spectroradiometer is calibrated according to irradiance. Hence, a diffusor type input optic with a defined entrance aperture is used in front of the spectroradiometer. Once calibrated, the detector head must not be removed from the spectroradiometer, as typically the calibration will be lost when the system is reassembled again.

The spectroradiometers sensitivity $s_{spec}(\lambda)$, i.e. calibration function of the spectroradiometer, can be derived from Equation (15):

$$s_{\mathrm{spec}}(\lambda) = y_{\mathrm{s,Ref}}(\lambda) \cdot S_{\mathrm{Ref}}^{-1}(\lambda) \cdot c_{\mathrm{Int}}(\lambda) \cdot c_{\mathrm{lin}}(\lambda) \cdot c_{\mathrm{bw}}(\lambda) \cdot c_{\mathrm{wl}}(\lambda) \cdot c_{\mathrm{T}}(\lambda) \quad (18)$$

where

$y_{\mathrm{s}}(\lambda)$: measured count signal, $(y_{\mathrm{s}}(\lambda) = y_{\mathrm{light}}(\lambda) - y_{\mathrm{dark}}(\lambda))$, of the spectroradiometer, Student-T-distribution based on the mean and the standard distribution of the repeated measurements with the number of readings represented by the degrees of freedom of the distribution, unit [count]

$S_{\mathrm{Ref}}(\lambda)$: calibration value of the density of spectral irradiance of the reference source at the set distance. Ideally provided with a correlation matrix of dimension N with $\lambda_1 \leq \lambda \leq \lambda_N$ so that the spectral irradiance can be treated as a correlated N-dimensional multivariate quantity within the Monte Carlo simulation. Normally it would be stated in the calibration certificate that the single $S_{\mathrm{Ref}}(\lambda)$ values will follow a Gaussian distribution, unit [$\mathrm{Wm^{-2}nm^{-1}}$]

$c_{\mathrm{Int}}(\lambda)$: spectral correction factor for the integration time, Gaussian distributed, unit: [-]

$c_{\mathrm{bw}}(\lambda)$: spectral correction factor for the bandwidth, Uniform distributed, unit: [-]

$c_{\mathrm{lin}}(\lambda)$: spectral correction factor for the linearity, Gaussian distributed, unit: [-]

$c_{\mathrm{wl}}(\lambda)$: spectral correction factor for the wavelength calibration, Gaussian distributed, unit: [-]

$c_{\mathrm{T}}(\lambda)$: spectral correction factor for the temperature, Uniform distributed, unit: [-]

Note: $y_{\mathrm{s}}(\lambda)$ is the measured signal reduced by the signal of the internal and external stray light. The external stray light signal can be easily determined by shading the light falling directly into the aperture of the input optics to measure the effect of indirect stray light, while the internal stray light can at least be estimated by using blocking or band-pass filters in front of the input optics to let through only light in the spectral range from 360 nm to 830 nm.

4.8.2.1.2 Model of evaluation for photometric data

Equation (10) and equation (14) allow for the measured source to determine the best estimate of the luminous intensity and its uncertainty. In practice, these equations are reformulated as:

$$I_{\mathrm{v}} = \frac{d^2}{\Omega_0} \cdot \frac{J_{\mathrm{Ph}}}{s_{\mathrm{v}}} \cdot \frac{\sum_{i=0}^{N_\lambda-1} S(\lambda_i) \cdot V(\lambda_i) \cdot (\lambda_{i+1} - \lambda_i)}{\sum_{i=0_1}^{N_\lambda-1} S(\lambda_i) \cdot s_{\mathrm{rel,C}}^{*}(\lambda_i) \cdot (\lambda_{i+1} - \lambda_i)} \tag{19}$$

where the index i stands for the i-th wavelength step if the wavelength range is divided into N_λ steps, starting with $i = 0$ at e.g. $\lambda_0 = 360\ \mathrm{nm}$. The distribution of relative responsivity $s_{\mathrm{rel,C}}^{*}$ of the calibrated photometer has to be provided by the manufacturer or measured separately. To solve this equation, the mean values of the measured input quantities are used.
In case of the direct determination of the luminous intensity using a spectroradiometer, equation 14 is transformed into:

$$I_{\mathrm{v}} = \frac{d^2}{\Omega_0} \cdot K_{\mathrm{m}} \sum_{i=0}^{N_\lambda-1} y_{\mathrm{s}}(\lambda_i) \frac{1}{s_{\mathrm{spec}}(\lambda_i)} \cdot V(\lambda_i) \cdot (\lambda_{i+1} - \lambda_i) \tag{20}$$

where $s_{\mathrm{spec}}(\lambda_i)$ is given by equation (18).

4.8.2.1.3 Implementation of Monte Carlo Method

The determination of the uncertainty of the luminous intensity provided by equation 17 or equation 18 can easily be done using a Monte Carlo Method. When applying Monte Carlo Method with spectral data, it is most convenient to describe the spectral data by a line vector. For spectral data with N_λ elements(e.g. from 360nm to 830 nm in 5 nm steps → $N_\lambda = 95$):

$$\boldsymbol{S} = [S_0, S_1, S_2, \dots, S_{N_\lambda-1}] \tag{21}$$

As there is typically an uncertainty in wavelength, we can also define a wavelength vector:

$$\boldsymbol{\lambda} = [\lambda_0, \lambda_1, \lambda_2, \dots, \lambda_{N_\lambda-1}] \tag{22}$$

In the Monte Carlo procedure, random numbers are generated that simulate the dispersion of each input variable given in equation (19) and equation (20) according to its uncertainty. For example in case of $S_{\mathrm{Ref}}(\lambda)$ as an input quantity of $s_{\mathrm{spec}}(\lambda_i)$ in equation 18 we will get for one draw of the vector:

$$\boldsymbol{S}_{\mathrm{r,Ref}} = \left[(1+\delta_0 u_{\mathrm{Ref,0}})S_{\mathrm{Ref,0}}, (1+\delta_1 u_{\mathrm{Ref,1}})S_{\mathrm{Ref,1}}, \dots, (1+\delta_0 u_{\mathrm{Ref},N_\lambda-1})S_{\mathrm{Ref},N_\lambda-1}\right] \tag{23}$$

with

$\boldsymbol{S}_{\mathrm{r,Ref}}$: a random draw of the calibrated irradiance, represented in vector notation

$\delta_0, \delta_1, \dots$: random numbers drawn in the range $0 \le \delta_i \le 1$.

$u_{\mathrm{Ref},i}$ wavelength dependent uncertainty of the spectral irradiance (here, provided by the calibration sheet)

$S_{\mathrm{Ref},i}$: mean value of the spectral irradiance data at a given wavelength

Note 1: If all δ_i with $0 \leq i \leq (N_\lambda - 1)$ for a single draw of the vector quantity are represented by the same random number, the vector elements of the vector quantity are expected to be fully correlated. If all δ_i for a single draw of the vector quantity are themselves drawn randomly, the vector elements of the vector quantity are expected to be totally uncorrelated. If there is a systematic distribution among the δ_i, the vector elements of the vector quantity are expected to be partially correlated.

Note 2: The distribution of the δ_i has to follow the distribution of measured quantity, i.e. whether the quantity is normal, uniform or Student T-distributed. In many cases it is sufficient to assume either normal or uniform distributions.

When using this nomenclature, equation (19) and (20) will transform into:

$$I_{\mathrm{r,v}} = \frac{d_r^2}{\Omega_0} \cdot \frac{J_{\mathrm{r,Ph}}}{s_{\mathrm{r,v}}} \cdot \frac{\sum_{i=0}^{N_\lambda - 2} S_r(\lambda_{r,i}) \cdot V(\lambda_{r,i}) \cdot (\lambda_{r,i+1} - \lambda_{r,i})}{\sum_{i=0}^{N_\lambda - 2} S_r(\lambda_{r,i}) \cdot s_{\mathrm{rel,C}}^*(\lambda_{r,i}) \cdot (\lambda_{r,i+1} - \lambda_{r,i})} \tag{24}$$

and

$$I_{\mathrm{r,v}} = \frac{d_r^2}{\Omega_0} \cdot K_{\mathrm{m}} \sum_{i=0}^{N_\lambda - 2} y_{\mathrm{r,s}}(\lambda_{r,i}) \frac{1}{s_{\mathrm{spec}}(\lambda_{r,i})} \cdot V(\lambda_{r,i}) \cdot (\lambda_{r,i+1} - \lambda_{r,i}) \tag{25}$$

Finally, the best estimate of the luminous intensity is derived by multiple e.g. $M = 10.000$ draws of equation (24) or (25), with e.g. $1 \leq r \leq 10.000$:

$$\overline{I_{\mathrm{v}}} = \frac{1}{M} \sum_{r=1}^{M} I_{r,\mathrm{v}} \tag{26}$$

with the associated standard uncertainty:

$$u(I_{\mathrm{v}}) = \sqrt{\frac{1}{M-1} \sum_{r=1}^{M} \left(I_{r,\mathrm{v}} - \overline{I_{\mathrm{v}}}\right)^2} \tag{27}$$

4.8.2.2 Chromaticity coordinates

To determine the chromaticity coordinates (x, y) the tristimulus values X, Y, Z must be determined before. With $V(\lambda) = \bar{y}(\lambda)$ the tristimulus values result analogous to equation (13) and equation (15)

$$X = \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot \bar{x}(\lambda) \cdot \mathrm{d}\lambda \tag{28}$$

$$Y = \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot \bar{y}(\lambda) \cdot \mathrm{d}\lambda \tag{29}$$

$$Z = \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot \bar{z}(\lambda) \cdot \mathrm{d}\lambda \tag{30}$$

where $S(\lambda)$ is the spectral distribution of the light source measured.

From these, the chromaticity coordinates x and y can be determined according to:

$$x = \frac{X}{X + Y + Z} \tag{31}$$

and

$$y = \frac{Y}{X + Y + Z} \tag{32}$$

4.8.2.2.1 Model of evaluation

Instead of equation (20), the very similar formulars based on the colour matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ must be solved instead of $V(\lambda)$:

$$X = \sum_{i=0}^{N_\lambda - 1} y_\mathrm{s}(\lambda_i) \frac{1}{s_\mathrm{spec}(\lambda_i)} \cdot \bar{x}(\lambda_i) \cdot (\lambda_{i+1} - \lambda_i) \tag{33}$$

$$Y = \sum_{i=0}^{N_\lambda - 1} y_\mathrm{s}(\lambda_i) \frac{1}{s_\mathrm{spec}(\lambda_i)} \cdot \bar{y}(\lambda_i) \cdot (\lambda_{i+1} - \lambda_i) \tag{34}$$

$$Z = \sum_{i=0}^{N_\lambda - 1} y_\mathrm{s}(\lambda_i) \frac{1}{s_\mathrm{spec}(\lambda_i)} \cdot \bar{z}(\lambda_i) \cdot (\lambda_{i+1} - \lambda_i) \tag{35}$$

with

$y_\mathrm{s}(\lambda_i)$: measured count signal, ($y_\mathrm{s}(\lambda_i) = y_\mathrm{light}(\lambda_i) - y_\mathrm{dark}(\lambda_i)$), of the spectroradiometer at a given wavelength, Student-T-distribution based on the mean and the standard distribution of the repeated measurements with the number of readings represented by the degrees of freedom of the distribution, unit [count]

$s_\mathrm{spec}(\lambda_i)$: sensitivity of spectroradiometer, i.e. the spectral calibration factor for spectral irradiance at the given wavelength, unit [count m² nm W^{-1}]

N_λ: Number of wavelength steps used for the measurement, unit [-].

λ_i: centroid wavelength at a given wavelength step, unit [nm].

4.8.2.2.2 Determination of correlations

The chromaticity coordinate (x, y) is a multivariate quantity, which means that it consist of more than one output quantities. In Addition, the two elements x and y of this bivariate chromaticity coordinate are correlated with respect to each other due to the same series of measurement of the spectral distribution of the light source and overlapping colour matching functions. In order to determine the correlation index between the x and y coordinate, the spectral distribution of the light source, $S(\lambda)$, given by equation (15) must first be determined by a series of n independent measurements. For each of the $1 \le j \le n$ distributions the quantities X_j, Y_j, Z_j, x_j, y_j and the associated mean values $\overline{X_n}, \overline{Y_n}, \overline{Z_n}, \overline{x_n}, \overline{y_n}$ must be calculated, so that finally the correlation coefficient is determined by:

$$r(\overline{x_n}, \overline{y_n}) = \frac{\sum_{j=1}^{n}(x_j - \overline{x_n}) \cdot (y_j - \overline{y_n})}{\sqrt{\sum_{j=1}^{n}(x_j - \overline{x_n})^2 \cdot \sum_{j=1}^{n}(y_j - \overline{y_n})^2}} \tag{36}$$

which results in the correlation matrix for the two-dimensional chromaticity coordinate:

$$\boldsymbol{\rho} = \begin{pmatrix} 1 & r(\overline{y_n}, \overline{x_n}) \\ r(\overline{x_n}, \overline{y_n}) & 1 \end{pmatrix} \tag{37}$$

However, if the spectral uncertainty components required for equation (18) to determine $s_{\mathrm{spec}}(\lambda_i)$ and the uncertainty of the wavelength scale are known, a set of n distributions of $S(\lambda)$ can also be drawn by Monte Carlo simulation using the route provide in 4.8.2.1.3. In this way, it is easy to provide large numbers of independent spectral distributions for the determination of the correlation matrix.

4.8.2.2.3 Influence of correlation on chromaticity coordinates

If no correlations are taken into account when determining the colour coordinates, both probability distribution functions (PDF) for x and y are independent. As the standard deviation of the spectral distribution of the light source is the same for x and y, the distribution of possible colour coordinates will appear in the two-dimensional colour space as a circular cloud around the (x, y)-coordinate. However, in practice, not only the standard deviation of the spectral distribution of the light source is the same for x and y, but also its actual representation. If at some wavelength the sum in equation (28) is increased due to fluctuations of the count signal, then also equation (29) will be increased. This leads to an ellipsoidal behaviour of the distribution of possible measurement values in the two-dimensional colour space (see Figure 3)

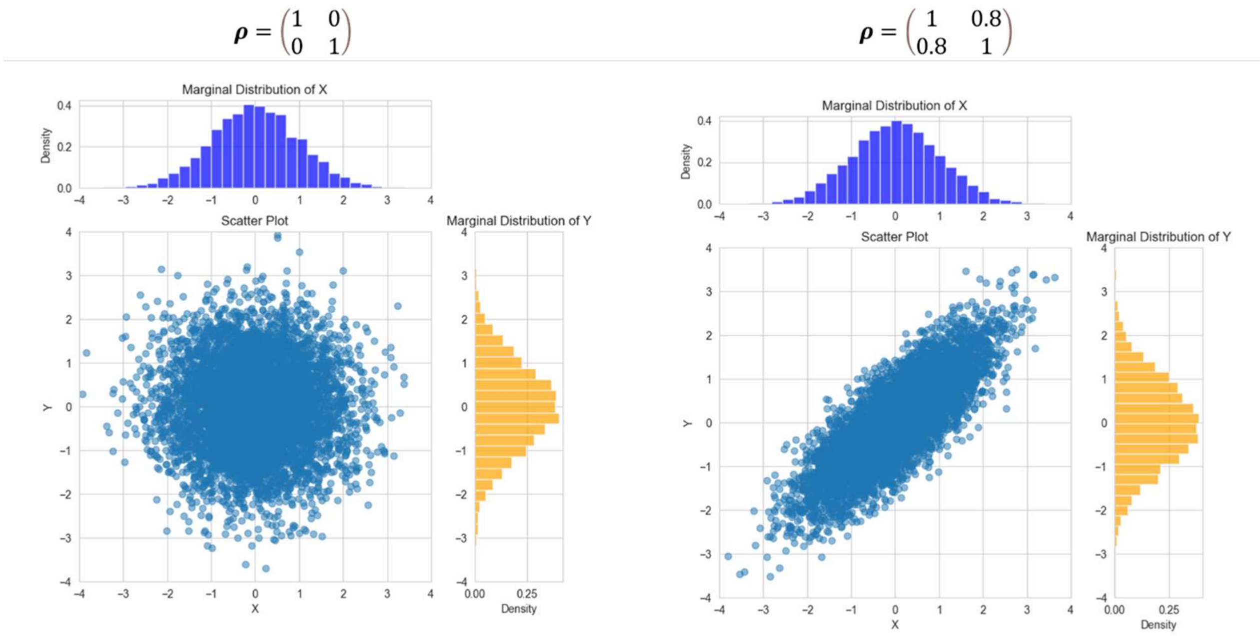

Figure 3 Effect of correlation on the colour coordinate.

As a result of the correlation of bivariate quantities, the typical expansion factor k (i.e. for an infinite degree of freedom $DoF \to \infty$) increases form $k = 2$ to $k = 2{,}45$.

5 Luminous flux based on integral and spectral measurements

This working procedure is intended for the calibration of LED lamps, single LEDs or LED based luminaires or modules (abbr. LED). This procedure can also be used for reference LED-based luminous flux lamps or incandescent lamps with an LED spectrum correcting filter, provided that these reference lamps are stable and reproducible.

5.1 Description of procedures for using integrating spheres

5.1.1 Methods for measuring luminous flux of LEDs in integrating spheres

There are two methods to measure the luminous flux of an LED: with an integrating sphere photometer or a goniophotometer (see chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**). To measure the spectral luminous flux, a spectroradiometer connected to the integrating sphere can be used. The simplest option is the relative measurement of the integral luminous flux with an integrating sphere photometer or a goniophotometer using a photometer (luxmeter) against a calibrated reference standard. For the relative spectral total radiant power, a spectroradiometer is also required. Absolute spectral measurements are problematic due to the complexity of capturing all measurement uncertainty contributions; this is easier with photometers that set spectral dependencies in fixed relationships via an optical filter and are corrected to V(λ) with respect to their spectral responsivity.

When using a goniometer, the illuminance of the LED radiation is measured in all directions, the measurement results are processed, and the luminous flux is calculated. In practice, the illuminance distribution is "scanned" on a virtual sphere around the source, whereby the spatial resolution of the measurement points must be higher the more structured the illuminance distribution of the source is. In general, for sphere and goniophotometer measurements, the relative spectral sensitivity of the photometer should be very well matched to V(λ) to reduce spectral mismatches. In addition, the spectral characteristic of the illuminance of the reference lamp used for the calibration of the photometer should be as similar as possible to the spectral distribution of the LED source to be measured and the reference source for the subsequent sphere measurement.

The calibration of an integrating sphere photometer (i.e. the joint calibration of sphere properties and detector properties) to measure solid state lighting products (SSL) like LEDs can be performed by irradiating a known directional luminous flux from outside through a sphere port or via the total luminous flux of a reference lamp mounted in the centre or at the wall of the sphere (see Figure 4). The last possibility is only mentioned for completeness but will not be described in detail here.

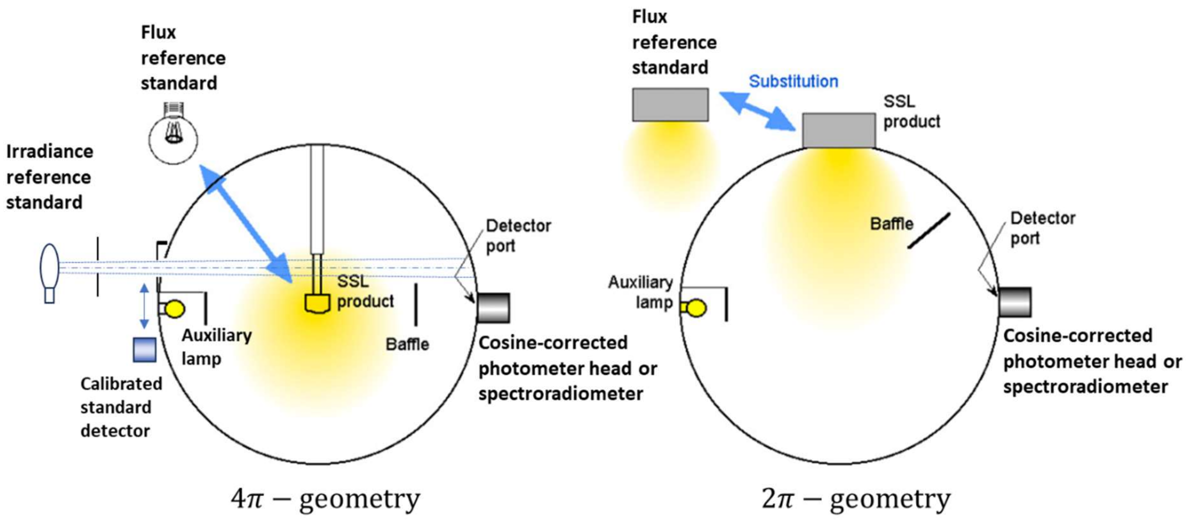

Figure 4 Calibration possibilities using integrating spheres.

In the second case, the signal of the integrating sphere photometer is measured for the known luminous flux of the reference lamp and the responsivity of the integrating sphere photometer is determined. It should be noted that a shutter inside the sphere between the measuring lamp and the detector ensures that no direct radiation from the reference lamp hits the detector of the integrating sphere photometer. After calibrating the sphere photometer, the LED source to be measured is then inserted into the integrating sphere photometer instead of the reference lamp, and the luminous flux of the LED is determined using the previously measured responsivity. However, this only works, if the spectral characteristic of the luminous flux of the reference lamp is very close to the spectral characteristic of the measured LED so that the sensitivity of the integrating sphere photometer is approximately the same for the LED and for the reference lamp. If this is not the case, a spectral mismatch calculation must be performed.

Instead of calibrating the sphere photometer with a luminous flux standard lamp, calibration can also be carried out with a highly stable luminous intensity standard lamp or illuminance standard lamp whose illuminance in a defined plane is known. Either a lamp with a mirror condenser or lens system that forms a converging light field is used - this light field must be determined in advance with a reference photometer with known spectral responsivity, or a highly stable illuminance reference source without optics may be used. In this case, the lamp must be located at the required distance in front of the entrance port of an integrating sphere photometer with a known aperture. The illuminance at this distance must in turn have been measured beforehand with a reference photometer (luxmeter) of known spectral responsivity. The decisive factor in this arrangement is that the input port of the sphere for the reference radiation is arranged in such a way that the first reflection of the directed luminous flux is seen by the detector of the integrating sphere photometer inside the sphere. The measured signal of the integrating sphere photometer is used to determine its responsivity with respect to the luminous flux. However, it should be noted that the light beam of the reference source incident through the port does not strike the sphere wall perpendicularly in the beam centre like the beam of the test source does, but at a certain angle. For this reason, the angle-dependent reflection of the sphere wall with respect to the entrance port must be precisely determined in advance in order to determine the necessary correction factor. Based on the measured responsivity of the sphere photometer, the next step is to measure the luminous flux of the LED to be measured, which is placed in the centre of the integrating sphere photometer. The spectral characteristic of the directional luminous flux of the reference lamp should again be close to the spectral characteristic of the measured LED, so that the responsivity of the integrating sphere photometer for the luminous flux of the LED and the directional luminous flux is approximately the same. If this is not the case, a spectral mismatch calculation must be performed.
According to sphere theory, the Measurement model to be used for the measurement using a photometer as detector is:

$$\Phi_{DUT} = \frac{J_{\mathrm{Ph}}(\lambda)}{J_{\mathrm{Ref}}(\lambda)} \cdot \Phi_{\mathrm{Ref}}(\lambda) \cdot c_{\mathrm{Aux}} \cdot c_F \cdot c_{SRF} \cdot c_{T,\mathrm{amb}} \cdot (1 + \Delta_{\mathrm{NA}} - \Delta_{\mathrm{Flour}}) \quad (38)$$

with

Φ_{DUT}: luminous flux of the device under Test (i.e. the LED)
Φ_{Ref}: luminous flux of the device under Test (i.e. the LED)
$J_{\mathrm{Ph/Ref}}$: Signal of the photometer for the measurement of the LED and the Reference lamp
c_{Aux}: Correction factor for the self-absorption ($= J_{\mathrm{Aux, Ref}} / J_{\mathrm{Aux, DUT}}$) measured with the auxiliary lamp
c_F: correction factor for the spectral mismatch (whole system) analogues to equation (11)(13)
c_{SRF}: correction factor for spatial response $\left(= f_{\mathrm{s, Ref}} / f_{\mathrm{s, DUT}}\right)$ if there is some knowledge about the luminous intensity distributions of the sources being compared and the spatial nonuniformity of the sphere (see equation (42))
$c_{T,\mathrm{amb}}$: correction factor for ambient temperature $\left(= \alpha_{\mathrm{Ref}} \cdot \Delta T_{\mathrm{amb, Ref}} / \alpha_{\mathrm{DUT}} \cdot \Delta T_{\mathrm{amb, DUT}}\right)$
Δ_{NA}: Near- field absorption (light which is emitted by the source and directly absorbed)
Δ_{Flour}: Fluorescence of the coating.

Regarding the correction factor, c_F , for the spectral mismatch it is not sufficient to determine the spectral mismatch of the photometer. Also the spectral throughput of the sphere needs to be taken into account.

Since the sphere coating is not 100% homogeneous spectrally as well as spatially (see above), it is first important to determine the mean spectral distribution of the reference lamp outside the sphere. This can be done either with the help of a goniometer or (as a work around) via an auxiliary measurement by rotating the free-burning reference lamp outside the sphere in front of the diffuser input optic of a spectroradiometer and thus averaging at least one plane of the irradiance distribution of the reference lamp. The reference lamp is then placed in the centre of the integrating sphere and measured inside with the same spectroradiometer (e.g. replacing the photometer of the sphere). The sphere spectral throughput, $T_{\mathrm{s}}(\lambda)$, of the integrating sphere spectroradiometer is determined by comparing the measurements outside and inside the sphere:

$$\tau_{\mathrm{s}}(\lambda) = c \cdot \frac{E_1(\lambda)}{E_0(\lambda)} \quad (39)$$

with

$E_0(\lambda)$: mean value of the spectral irradiance measured through the diffusor optic of spectroradiometer when rotating the reference source outside the sphere.
$E_1(\lambda)$: value of the spectral irradiance of the reference source mounted in the centre of the sphere and measured with the same spectroradiometer as $E_0(\lambda)$.
c: normalisation factor.

Analogous to equation (11) the mismatch correction factor for the sphere is now determined as:

$$c_F = \frac{\int_{\lambda_1}^{\lambda_2} S_\mathrm{A}(\lambda) s_\mathrm{rel}(\lambda) \cdot \tau_\mathrm{s}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S_\mathrm{A}(\lambda)\, V(\lambda) d\lambda} \frac{\int_{\lambda_1}^{\lambda_2} S(\lambda) V(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, s_\mathrm{rel}(\lambda) \tau_\mathrm{s}(\lambda) d\lambda} \quad (40)$$

If it is not possible to use reference sources and devices under test having at least nearly the same relative luminous intensity distribution, the spatial response distribution function SRDF, $K(\theta,\phi)$, of the sphere should be determined to get at least an idea about the estimated deviations. This is usually done with sphere scanner, i.e. a rotating light beam (ideally coloured, to also account for spectral issues) yielding a map in (θ,ϕ) of deviations , K, of the uniformity of the sphere. The normalised SRDF is:

$$K^*(\theta,\phi) = \frac{4\pi \cdot K(\theta,\phi)}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} K(\theta,\phi) sin\theta \mathrm{d}\theta \mathrm{d}\phi} \quad (41)$$

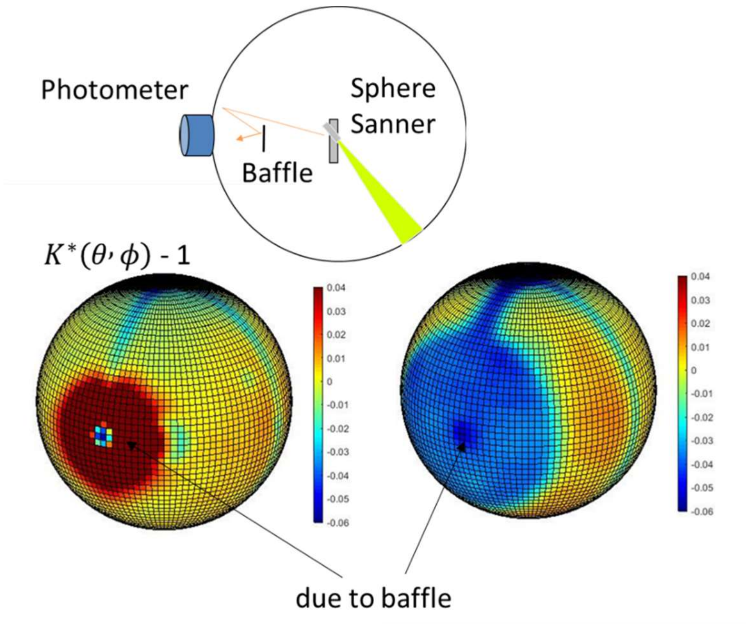

Figure 5 SRDF of an integration sphere

For a given relative angular luminous intensity distribution LID, $I_\mathrm{rel}(\theta,\phi)$, the sphere response factor, f_s, is determined according:

$$f_s = \frac{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} I_\mathrm{rel}(\theta,\phi) K(\theta,\phi) sin\theta \mathrm{d}\theta \mathrm{d}\phi}{\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} I_\mathrm{rel}(\theta,\phi) sin\theta \mathrm{d}\theta \mathrm{d}\phi} \quad (42)$$

Even if it would be not possible to determine the sphere response factor, f_s, due to the lack of knowledge regarding the LIDs, at least the knowledge of $K^*(\theta,\phi)$ is of benefit. For example, as a consequence of the non-uniformity of a sphere, as shown in Figure 5, it would therefore be advisable not to align the beam of an LED spot that is to be measured in the direction of the baffle or in the opposite direction to it, as in this case the measured value will be greatly over- or underestimated.

The last term in equation (38) can often be neglected by suitable design of the lamp holder (in case of near-field absorption) and by fluorescence-free coating of the sphere.

5.1.2 Spectral flux measurement of LED using an integrating sphere

For the measurement of the total spectral radiation flux (SF) of the LED, an integrating sphere spectroradiometer with input optics with diffuser embedded on the inner surface of the sphere is used. The calibration of an integrating sphere spectroradiometer can be performed both with a known total spectral radiant flux source with directed radiation (see above) and with a known total spectral radiant flux source as a reference lamp operated within the sphere. In the second case, the spectral sphere throughput of the sphere spectroradiometer must be determined in advance as shown in equation (39).

In the next step spectral radiant flux of the reference lamp to which the DUT is compared to is measured, where again direct light must be prevented from falling on the spectroradiometer by a suitable baffle.

With equation (39), the spectral distribution of the source installed in the integrating sphere measured with the spectroradiometer given in equation (15) becomes

$$S(\lambda) = \frac{y_S(\lambda)}{\tau_{\mathrm{s}}(\lambda) \cdot s_{\mathrm{spec}}(\lambda)} \qquad (43)$$

And the total spectral radiant flux of the device under test is given as

$$\Phi_{DUT}(\lambda) = \frac{S_{\mathrm{DUT}}(\lambda)}{S_{\mathrm{Ref}}(\lambda)} \cdot \Phi_{\mathrm{Ref}}(\lambda) \cdot c_{\mathrm{Aux}}(\lambda) \cdot c_{SRF}(\lambda) \cdot c_{T,\mathrm{amb}} \cdot (1 + \Delta_{\mathrm{NA}}(\lambda) - \Delta_{\mathrm{Flour}}(\lambda)) \qquad (44)$$

Finally, the total spectral radiant flux can be integrated to obtain the luminous flux:

$$\Phi_{\mathrm{v,DUT}} = K_{\mathrm{m}} \int_{\lambda_1}^{\lambda_2} \Phi_{DUT}\,(\lambda) \cdot V(\lambda) \mathrm{d}\lambda \qquad (45)$$

For Monte Carlo simulations and uncertainty assessments, the path described in chapter 4.8.1.1 can be followed.

5.2 Description of procedures for using goniometers

Using a goniometer, the luminous flux of a LED lamp is based on the measurement of the spatially distributed emitted light. The luminous intensity is measured in a set of directions defined according to spherical coordinates (Figure 6) and spatial integration allows to calculate the luminous flux. The relative spectral responsivity of the photometer should be close to $V(\lambda)$.

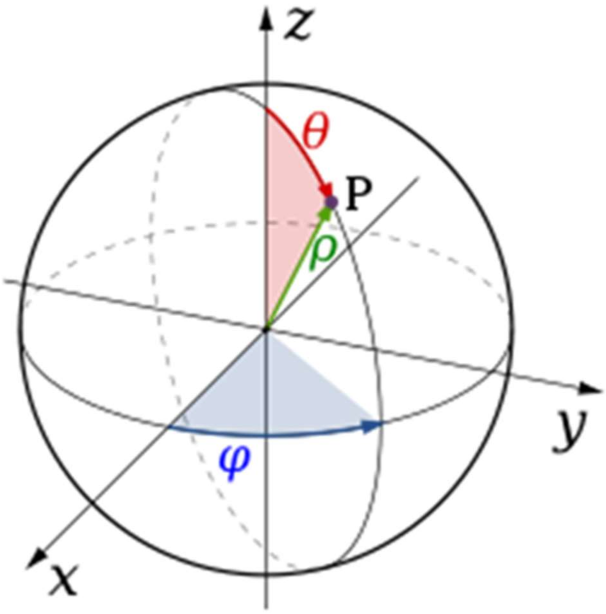

Figure 6 Spherical coordinates

When using a photometer calibrated in illuminance, the luminous intensity $I_{\mathrm{v}}(\varphi,\theta)$ for a given direction (φ,θ) is obtained by:

$$I_{\mathrm{v}}(\varphi,\theta) = d^2/\Omega_0 \cdot \left(J_{\mathrm{Ph}}(\varphi,\theta)\right)/s_{\mathrm{v}} \cdot F(\varphi,\theta) \qquad (46)$$

When using a (array-)spectroradiometer calibrated in spectral irradiance instead of a photometer, equation (46) simplifies to:

$$I_{\mathrm{v}}(\varphi,\theta) = d^2/\Omega_0 \cdot K_{\mathrm{m}\int(_{1}^{\lambda}}^{(\lambda_2)} y_{(s,(\varphi,\theta))}(\lambda) \cdot 1/\left(s_{\mathrm{spec}}(\lambda)\right) \cdot V(\lambda) d\lambda \qquad (47)$$

Based on the luminous intensity measurements the luminous flux Φ_{v} is given by:

$$\Phi_{\mathrm{v}} = \int_{\theta=0}^{\theta=\pi} \int_{\varphi=0}^{\varphi=2\pi} I_{\mathrm{v}}(\varphi,\theta) \cdot sin\theta \; d\theta \; d\varphi \qquad (48)$$

Where the angle $\theta = 0$ is along the z-axis.

5.2.1 Description of artefacts

The subjects of calibration are LED based Lamps, luminaires or modules, where also single LEDs may be considered as an LED lamp. They may be operated directly with DC current or by a built-in power supply, which is operated with AC voltage. The size and form of the LED lamp must fit properly into the holders of the setup, allowing all adjustments necessary to measure the quantities required. The maximum size of the artefact also depends on the maximum achievable distance between source and photometer/spectroradiometer. The photometric centre of the source must be defined prior to the measurement. Standard EN 13032-1:2004+A1:2012 (CEN, 2012) shows how to determine the photometric centre depending on the shape of the LED lamp.

5.2.2 Criteria for acceptance/rejection of artefacts

The LED lamp must show a stable and reproducible behaviour, so that it can be expected that the values measured will be valid also at the customer's site if the boundary conditions that were valid during the calibration are reproduced. The lamps must comply with the boundary condition specified in Section 5.2.5.

5.2.3 Parameters and quantities to be determined

The quantity to be determined is the luminous flux that requires the following quantities or parameters to be measured:

- The spatially distributed luminous intensity of the LED lamp
- The LED lamp current and voltage
- The LED lamp temperature
- The spectral distribution of the light source on the spectral range 360 nm to 830 nm, or at least from 380 nm up to 780 nm

Quantity such as the distance between the photometric centre and the photometer was measured when the goniophotometer was set-up and doesn't need to be measured again.

5.2.4 Required references

A list of measurement equipment used as references shall be kept, including:

- Calibrated photometer including its relative spectral responsivity.
- Calibrated spectroradiometer or array spectroradiometer:
    - amplitude calibrated against a spectral irradiance standard or calibrated against a spectrally calibrated LED Lamp with spectral distribution comparable to DUT.
    - wavelength calibrated using e.g. a set of Pen-Ray lamps to provide known line spectra for wavelength calibration of the spectroradiometer.
- Calibrated voltmeter to measure lamp voltage.
- Calibrated ammeter or a calibrated voltmeter and a calibrated shunt resistance to measure lamp current.

- Temperature gauge

Ideally, the correlation matrix or covariance matrix should be available for all distributions. However, please take into mind that measured covariance matrices tend to be ill conditioned and need to be adjusted so that they are positive semidefinite. In this respect, the precision of the data in the covariance matrix is important in such a way that the lower the precision the more likely that the matrix is ill conditioned.

5.2.5 Devices and equipment including technical requirements

5.2.5.1 Measurement set-up

Different types of goniophotometers are available depending on source/photometer configurations and position in space. The characteristics of the different types of goniophotometers are described in Table 1. For all types of goniophotometers the measurement requirements are the following:

1. Luminous intensity measurements are performed using a photometer or a spectroradiometer. (Instead of luminous intensity measurements also illuminance measurements are possible. In this case the integral in equation (48) is taken over the illuminance measurements $E_{\mathrm{v}}(\varphi, \theta)$ and need to be multiplied by d^2.)
2. In case of measurement using a calibrated photometer:
    a. Calibrated photometer with known relative spectral responsivity distribution. In case of using a type 3 goniophotometer, calibration of the photometer should take into account the mirror's spectral reflectivity.
    b. A calibrated nano-ammeter for the reference photometer (or a voltmeters in combination with a transimpedance amplifier connected to the photometer) with sufficient resolution (e.g. 5 1/2 digits) to measure the photometers outputs.
    c. Temperature controller for the reference photometer in order to be able to set the temperature of the detector specified in the calibration certificates.
3. In case of measurement using an (array-)spectroradiometer:
    a. Calibration light source for the amplitude calibration of the spectroradiometer: In most cases a tungsten halogen lamp for the visible spectral range (e.g. 1000W FEL type lamp) is used and placed at the required calibration distance in front of the spectroradiometer to be calibrated. In case of using a type 3 goniophotometer, calibration of the spectrometer should take into account the mirror's spectral reflectivity.
    b. Stable current source for the calibration lamp (e.g. Output: 10A/140V in case of a 1000 W FEL type lamp) with an output drift of less than $1 \cdot 10^{-4}\ \mathrm{h}^{-1}$.

   c. A series of spectral line sources (e.g. pen-ray light sources) that can be installed sequentially on the optical axis of the spectroradiometer to calibrate the wavelength scale of the spectroradiometer in the required range from 360 nm to 830 nm (but at least 380 nm to 780 nm).

4. Stable current or voltage source for the DUT (type of power source depends on the DUT to be measured) with an output drift of less than $1 \cdot 10^{-4}\ \mathrm{h}^{-1}$.
5. Temperature sensor to monitor the ambient temperature of the measurement setup.

Table 1: Types of goniophotometers

Gonio photo meter	Configuration	Characteristics	Comments
Type 1	The light source is rotated around a vertical as well as a horizontal axis. The photometer head is fixed.	Type 1.1 – fixed horizontal axis, – movable vertical axis – measurement B-planes	Measurements are possible only for light sources, which can be used in any orientation and whose relative luminous intensity distribution does not change with burning position. Measurements of light sources with burning position dependent luminous flux are possible. If the operating orientation differs from the standard burning position, a correction of the measurement values is necessary. This can be determined with a auxiliary photometer, as long as its photometer head does not change direction and distance to the light source during movement, so that changes of the luminous flux by a change of burning position result in a proportional photo current.
		Type 1.2 – fixed vertical axis, – movable horizontal axis – measurement in B planes	
		Type 1.3 – fixed vertical axis, – movable horizontal axis – measurement in C planes	
Type 2	The light source is rotated around a vertical axis and the photometer head is moved	Type 2.1 – fixed vertical axis, – movable horizontal axis – measurement in C planes	
		Type 2.2 Light source and photometer head are situated on different ends of rotation axis	
		Type 2.3 Moving of the photometer head on a straight line, (e.g. horizontal and/or vertical).	
Type 3	The light source is rotated around a vertical axis, a mirror arrangement around a horizontal axis. The photometer head is fixed.	Type 3.1 – centre of mirror in rotation centre – light source is rotated around the mirror on a fixed radius	The mirrors shall not limit the view of the light source from the photometer head and have to be plane. They should have a spectrally constant reflectance or their spectral reflectance shall be considered for the V(λ) correction of the used
		Type 3.2	

		– light source in rotation centre – the mirror is rotated around the light source on a fixed radius Type 3.3 light source and mirror are led on two oppositely orientated fixed radii around the rotation centre	photometer head. Attention shall be paid to the polarization of the radiation due to reflection by the mirrors and the local situation of the reflection.
Type 4	The light source is fixed and can be kept in any burning position		The photometer head is moved on a virtual sphere, in whose centre point the centre of the light source is located

5.2.6 Software

To allow for the propagation of correlation a Monte Carlo Method is used to calculate the expected values and the uncertainty of the requested quantities. The Monte Carlo Method uses the model of evaluation where the input variables of this model are randomly varied according to their probability distributions. If two input variables are correlated, a modified probability distribution is used based on the marginal distributions and the correlation matrix of the correlated quantities.

5.3 Data to be documented

Besides the calibrated luminous flux and its combined expanded uncertainty the nominal current and voltage of the LED source as well as its operating temperature shall be documented if the data can be made available. In addition, the spectral range used for the determination of the integral photometric value as well as the spatially distributed luminous intensity values must be reported. The spatially distributed luminous intensity values must be formatted according to the standard EN 13032-1.

5.4 Measurement procedure

Luminous flux measurement of LED lamps using a goniophotometer is performed according to the following steps:

- Switch-on all electronic devices and let them warm-up for at least 1 hour before taking measurements.

- Mount the LED lamp on the goniophotometer in its working position and align the photometric center of the LED lamp to the photometric center of the goniophotometer
- Switch-on the light source and set the proper supplied current or voltage
- Select the proper measurement software provided by the manufacturer of the goniophotometer
- Using the software set the measurement parameters in order to fulfil the requirements of the standard CIE S025 regarding the air speed and angle steps for both axes.
- Perform the measurement using the software when the LED lamp has reached output stability

Prior to performing the measurement the photometer or the spectroradiometer should be calibrated.

6 References

19NRM02 (2023) *Coding-Examples on GitHub repository .* https://github.com/empir19nrm02/empir19nrm02.

CEN (2012) *EN 13032-1+A1 Measurement and presentation of photometric data of lamps and luminaires Part 1: Measurement and file format.*

CIE (2018) *CIE 198 SP2:2018 Determination of Measurement Uncertaities in Photometry Supplement 2: Spectral measurements and derivative quantities.* CIE.

Additional good References

[1] CIE TN 009:2019 The Use of "Accuracy" and Related Terms in the Specifications of

[2] JCGM 100:2008, https://www.bipm.org/en/publications/guides/gum.html

[3] JCGM 101:2008, https://www.bipm.org/en/publications/guides/gum.html

[4] JCGM 102:2011, https://www.bipm.org/en/publications/guides/gum.html

[4] CIE 198:2011 Determination of Measurement Uncertainties in Photometry

[5] CIE 198-SP1.(1-4):2011 Determination of Measurement Uncertainties in Photometry - Supplement 1: Modules and Examples for the Determination of Measurement Uncertainties (4 Parts)