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TECHNICAL REPORT

Spectroradiometric Measurement of Optical Radiation Sources

CIE 250:2022

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This Technical Report has been prepared by CIE Technical Committee (TC) 2-80 of Division 2 "Physical Measurement of Light and Radiation" and has been approved by the Board of Administration and Division 2 of the Commission Internationale de l'Eclairage. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory.

Ce rapport technique a été élaboré par le Comité Technique (TC) 2-80 de la CIE Division 2 "Mesures Physiques de la Lumière et des Radiations" et a été approuvé par le Bureau et Division 2 de la Commission Internationale de l'Eclairage. Le document expose les connaissances et l'expérience actuelles dans le domaine particulier de la lumière et de l'éclairage décrit ici. Il est destiné à être utilisé par les membres de la CIE et par tous les intéressés. Il faut cependant noter que ce document est indicatif et non obligatoire.

Dieser Technische Bericht ist vom Technischen Komitee (TC) 2-80 der CIE Division 2 "Physikalische Messungen von Licht und Strahlung" ausgearbeitet und vom Vorstand sowie Division 2 der Commission Internationale de l'Eclairage gebilligt worden. Das Dokument berichtet über den derzeitigen Stand des Wissens und Erfahrung in dem behandelten Gebiet von Licht und Beleuchtung; es ist zur Verwendung durch CIE-Mitglieder und durch andere Interessierte bestimmt. Es sollte jedoch beachtet werden, dass das Dokument eine Empfehlung und keine Vorschrift ist.

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SPECTRORADIOMETRIC MEASUREMENT OF OPTICAL RADIATION SOURCES

Summary

This technical report provides basic measurement principles and practical guidance on spectroradiometry of optical radiation sources in the wavelength range from 200 nm to 2 500 nm and a detailed overview of physical effects relevant for measurement uncertainty estimation.

This document cancels and replaces CIE 063-1984. Additional details on measurement principles not covered in this document can be found in CIE 214:2014.

MESURE SPECTRORADIOMETRIQUE DES SOURCES DE RAYONNEMENT OPTIQUE

Résumé

Ce rapport technique fournit des principes de mesure de base et des conseils pratiques sur la spectroradiométrie des sources de rayonnement optique dans la gamme de longueur d'onde de 200 nm à 2 500 nm, ainsi qu'un aperçu détaillé des effets physiques pertinents pour l'estimation de l'incertitude de mesure. Des détails supplémentaires sur les principes de mesure qui ne sont pas couverts dans ce document peuvent être trouvés dans la CIE 214:2014.

Ce document annule et remplace CIE 063-1984.

Spektralradiometrische Messung von optischen Strahlungsquellen

Zusammenfassung

Dieser technische Bericht enthält grundlegende Messprinzipien und praktische Hinweise zur Spektralradiometrie optischer Strahlungsquellen im Wellenlängenbereich von 200 nm bis 2 500 nm sowie einen detaillierten Überblick über physikalische Effekte, die für die Abschätzung der Messunsicherheit relevant sind. Weitere Einzelheiten zu Messprinzipien, die in diesem Dokument nicht behandelt werden, sind in CIE 214:2014 zu finden.

Dieses Dokument annulliert und ersetzt CIE 063-1984.

1 Introduction

This report is primarily concerned with measurements of irradiance, radiance, radiant intensity, radiant flux and derived quantities in the ultraviolet, visible and near infrared regions of the electromagnetic spectrum in the wavelength range from 200 nm to 2 500 nm.

Intended as a basic document on spectroradiometry, the report makes reference to specific types of instrumentation or technology used in spectroradiometric measurements only where necessary for understanding of the text or for illustration purposes.

This report provides a detailed overview of relevant terminology and basic measurement principles, including those for instrument calibration. It provides practical guidance for identifying, understanding and quantifying relevant measurement uncertainty components.

2 Terms and definitions

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

CIE maintains a terminology database for use in standardization and other documents at the following address:

- CIE S 017, ILV: International Lighting Vocabulary: online available at <https://cie.co.at/e-ilv>.

2.1 spectroradiometer

instrument for measuring radiometric quantities in narrow wavelength intervals over a given spectral region

Note 1 to entry: This entry was numbered 845-05-07 in IEC 60050-845:1987.

Note 2 to entry: This entry was numbered 17-1236 in CIE S 017:2011.

[SOURCE: CIE S 017:2020, 17-25-007]

2.2 spectrum

display or specification of the monochromatic components of the radiation considered

Note 1 to entry: There are line spectra, continuous spectra, and spectra exhibiting both these characteristics.

Note 2 to entry: The term "spectrum" is also used for spectral efficiencies (excitation spectrum, action spectrum).

Note 3 to entry: This entry was numbered 845-01-08 in IEC 60050-845:1987.

Note 4 to entry: This entry was numbered 17-1238 in CIE S 017:2011.

[SOURCE: CIE S 017:2020, 17-21-015]

2.3 optical radiation

electromagnetic radiation at wavelengths between the region of transition to X-rays ($\lambda \approx 1$ nm) and the region of transition to radio waves ($\lambda \approx 1$ mm)

Note 1 to entry: This entry was numbered 845-01-02 in IEC 60050-845:1987.

Note 2 to entry: This entry was numbered 17-848 in CIE S 017:2011.

Note 3 to entry (only valid for this document): It should be noted that terms such as "UV light" and "infrared light" are commonly used, although not recommended by CIE. However, technically the term "light" only includes visible wavelengths (ILV, 17-21-012 (CIE 2020a)).

[SOURCE: CIE S 017:2020, 17-21-002, modified – Note 3 added]

2.4

stray light

unwanted light that forms part of the measurement

EXAMPLE Light that reaches the detector from directions other than the desired path from the source to the detector, e.g. light scattered from walls, ceilings or optical components within the measuring system. Light that reaches the detector which is at a wavelength other than the wavelength intended to be measured.

Note 1 to entry: This entry was numbered 17-1273 in CIE S 017:2011.

Note 2 to entry (only valid for this document): In this document the term "stray light" is also used for radiation outside the visible wavelength range.

[SOURCE: CIE S 017:2020, 17-25-116, modified – Note 2 added]

2.5

spectral distribution

X_λ

density of a radiant or luminous or photon quantity, $X(\lambda)$, with respect to wavelength, λ , at the wavelength λ

$$X_\lambda = \frac{dX(\lambda)}{d\lambda}$$

Note 1 to entry: The term "spectral distribution" is to be preferred to the equivalent term "spectral concentration" when dealing with the function $X_\lambda(\lambda)$ over a range of wavelengths, not at a particular wavelength.

Note 2 to entry: Usually X_λ is also a function of λ and in this case, in order to stress this, can be written $X_\lambda(\lambda)$ without any change of meaning.

Note 3 to entry: The spectral distribution of radiant flux is expressed in watt per nanometre ($\text{W}\cdot\text{nm}^{-1}$), the spectral distribution of luminous flux is expressed in lumen per nanometre ($\text{lm}\cdot\text{nm}^{-1}$), the spectral distribution of photon flux is expressed in nanometre to the power minus one (nm^{-1}). The units of spectral distributions of other quantities are expressed accordingly.

Note 4 to entry: The quantity X can also be expressed as a function of frequency, ν , wavenumber, σ , etc.; the corresponding symbols are $X(\nu)$, $X(\sigma)$, etc. and the corresponding densities with respect to frequency, ν , wavenumber, σ , etc. are X_ν , X_σ , etc., in which case the expression of units will also change accordingly.

Note 5 to entry: This entry was numbered 845-01-17 in IEC 60050-845:1987.

Note 6 to entry: This entry was numbered 17-1213 and 17-1212 in CIE S 017:2011.

[SOURCE: CIE S 017:2020, 17-21-029]

2.6

spectral radiant flux spectral radiant power

$\Phi_\lambda(\lambda)$

density of radiant flux, $\Phi_e(\lambda)$, with respect to wavelength, λ

Note 1 to entry: The definition of spectral radiant flux is independent of a particular region in space over which it is evaluated. Unambiguous interpretation of radiant flux values therefore requires also information about the region of evaluation, e.g. area, solid angle, volume.

Note 2 to entry: The spectral radiant flux emitted by a source into the solid angle $\Omega = 4\pi$ sr is called total spectral radiant flux (also called 4π radiant flux). The spectral radiant flux of a source emitted into the solid angle $\Omega = 2\pi$ sr is called 2π radiant flux (also called forward radiant flux).

Note 3 to entry: The spectral radiant flux is expressed in watt per nanometre ($\text{W}\cdot\text{nm}^{-1}$).

2.7

spectral irradiance

$E_{\text{e},\lambda}$; E_{λ}

density of irradiance, $E_{\text{e}}(\lambda)$, with respect to wavelength, λ

$$E_{\text{e},\lambda} = \frac{\text{d}E_{\text{e}}(\lambda)}{\text{d}\lambda}$$

Note 1 to entry: The spectral irradiance is expressed in watt per square metre per nanometre ($\text{W}\cdot\text{m}^{-2}\cdot\text{nm}^{-1}$).

Note 2 to entry: This entry was numbered 17-1217 in CIE S 017:2011.

[SOURCE: CIE S 017:2020, 17-21-056]

2.8

spectral radiant intensity

$I_{\lambda}(\lambda)$

density of radiant intensity, $I_{\text{e}}(\lambda)$, with respect to wavelength, λ

Note 1 to entry: The spectral radiant intensity is expressed in watt per steradian per nanometre ($\text{W}\cdot\text{sr}^{-1}\cdot\text{nm}^{-1}$).

2.9

spectral radiance

$L_{\text{e},\lambda}$, L_{λ}

density of radiance, $L_{\text{e}}(\lambda)$, with respect to wavelength, λ

$$L_{\text{e},\lambda} = \frac{\text{d}L_{\text{e}}(\lambda)}{\text{d}\lambda}$$

Note 1 to entry: The spectral radiance is expressed in watt per square metre per nanometre per steradian ($\text{W}\cdot\text{m}^{-2}\cdot\text{nm}^{-1}\cdot\text{sr}^{-1}$).

Note 2 to entry: This entry was numbered 17-1228 in CIE S 017:2011.

[SOURCE: CIE S 017:2020, 17-21-052]

3 Measurement of spectroradiometric quantities

3.1 Measurement principles

3.1.1 General

The spectral distribution, $X_{\lambda}(\lambda)$, of the radiometric quantity, X , assigned to a source spectrum entering the entrance optics of a spectroradiometer is recorded, with given resolutions in wavelength and signal amplitude, and the resulting measured signal is the product of the source spectrum, the throughput of the detection system including the optical extent, transmission and reflection losses, efficiency of the spectrally selective unit (see A.1.3) and the spectral responsivity of the detector. The range of wavelengths passed by a spectroradiometer with finite resolution at a given wavelength setting (or position in an array spectroradiometer) is determined by the line spread function (LSF), also known as the slit function, which is a convolution of the distribution of the optical radiation over the entrance and exit apertures. The

signal of the detector, $Y(\lambda)$, is therefore the convolution of an input spectral distribution, $X_\lambda(\lambda)$, with the instrument response function, $R(\lambda)$:

$$Y(\lambda) = X_\lambda(\lambda) * R(\lambda) \quad (1)$$

For a broadband source covering an extended range of wavelengths, the result of the convolution at a given wavelength λ_0 can be expressed as

$$Y(\lambda_0) = s(\lambda_0) \int_{-\infty}^{\infty} X_\lambda(\lambda) b(\lambda - \lambda_0) d\lambda \quad (2)$$

where $s(\lambda_0)$ is the instrument responsivity to monochromatic radiation at wavelength λ_0 (see 3.1.3 and $b(\lambda - \lambda_0)$ is the bandpass function (see 4.3).

3.1.2 Wavelength scale calibration

A spectroradiometer is designed to measure at a particular wavelength when the spectrally selective unit is set to a particular position or when reading the signal from a particular part of the detector array (see A.1.3). This is referred to as the nominal wavelength (of measurement), λ_0 . Calibration of the wavelength scale may alter the value assigned to that wavelength.

The centroid wavelength, λ_c , of the bandpass function, $b(\lambda - \lambda_0)$ (see 4.3) is given by

$$\lambda_c = \frac{\int \lambda b(\lambda - \lambda_0) d\lambda}{\int b(\lambda - \lambda_0) d\lambda} \quad (3)$$

The nominal wavelength a spectroradiometer is set to should be as close to the centroid wavelength as possible.

For a monochromatic source of wavelength λ_{line} , only that particular wavelength contributes to the integral of Equation (2). Treating the input spectrum as a delta function with value $X_\lambda(\lambda_{\text{line}})$ at the line wavelength, λ_{line} , and zero elsewhere, the measured signal at the set wavelength λ_0 becomes

$$Y(\lambda_0) = s(\lambda_0) \cdot X_\lambda(\lambda_{\text{line}}) \cdot b(\lambda_{\text{line}} - \lambda_0) \quad (4)$$

When varying the set wavelength, λ_0 , the measured spectrum is the reverse of the input bandpass over surrounding wavelengths (called line spread function (LSF)), as it would appear in a measurement of broadband sources. The bandpass function is defined in the spectral interval $(\lambda_{\text{line}} - \Delta \leq \lambda \leq \lambda_{\text{line}} + \Delta)$, where Δ is the spectral bandwidth. The function is assumed to go to zero outside this spectral interval (see 4.3.2.1 for more details).

Using monochromatic sources enables to minimize the difference $\lambda_{\text{line}} - \lambda_c$ for a variety of monochromatic lines. The wavelength scale should be determined using as many known wavelengths as possible. It can usually be based on a low-order polynomial fit

$$\lambda = \sum_k a_k \cdot p^k \quad (5)$$

where p is the position of the instrument indicating a wavelength and a_k are the fit coefficients.

Possible monochromatic sources for wavelength calibration are atomic emission sources (Hg, Ne, Xe, Ar, Kr, for examples see Annex A.2), laser lines, etalons and tunable sources such as high-resolution monochromators and tunable lasers.

Details on bandpass function and a possibility to correct for bandpass is given in CIE 214:2014 (CIE 2014). A detailed description of the principles and methods for wavelength calibration of spectroradiometers is given in CIE 233:2019 (CIE 2019).

3.1.3 Responsivity calibration

The spectral responsivity, $s(\lambda)$, of the spectroradiometer represents the response, $Y(\lambda)$, of the instrument to an incident spectral distribution, $X_\lambda(\lambda)$. When using tunable monochromatic optical radiation sources at wavelength λ_{line} of a known radiometric quantity, X_{ref} , the spectral responsivity of the instrument can be determined as

$$s(\lambda_{\text{line}}) = \frac{Y_{\text{ref}}(\lambda_{\text{line}})}{X_{\lambda, \text{ref}}(\lambda_{\text{line}})} \quad (6)$$

In this way, the determined instrument responsivity is valid only for monochromatic optical radiation sources. The responsivity determined does not represent the responsivity of the detector itself as it always comprises the normalization of the bandpass function. Especially for different bandwidths, the instrument responsivity will change.

For broadband sources, the calculation of the instrument responsivity accounts for the bandpass function of the instrument as well as for the variation of the detector spectral responsivity over the spectral bandpass, and from Equation (2) it follows for each set wavelength λ_0 :

$$s(\lambda_0) = \frac{Y(\lambda_0)}{\int X_\lambda(\lambda) b(\lambda - \lambda_0) d\lambda} \quad (7)$$

If the bandpass function, $b(\lambda - \lambda_0)$, is symmetrical around λ_0 over the spectral bandpass and the spectral responsivity of the detector is linear, the process can be simplified to some extent. Calibration of the responsivity is then achieved by measurement at time t_c of a reference source with known spectral distribution $X_{\lambda, \text{ref}}(\lambda, t_c)$:

$$s(\lambda, t_c) = \frac{Y_{\text{ref}}(\lambda, t_c)}{X_{\lambda, \text{ref}}(\lambda, t_c)} \quad (8)$$

The spectral distribution of a device under test (DUT) at a time t is then, by the same arguments that lead to Equation (8), given by

$$X_{\lambda, \text{DUT}}(\lambda, t) = \frac{Y_{\text{DUT}}(\lambda, t)}{s(\lambda, t_c)} \quad (9)$$

where t_c is the time of instrument calibration. If the responsivity of the spectroradiometer is stable in time, $s(\lambda, t_c) = s(\lambda, t) \equiv s(\lambda)$. The responsivity, $s(\lambda)$, stores the information of the reference source measurement and makes it available at a later time.

In general, the responsivity of a spectroradiometer should be calibrated separately for each spectroradiometric quantity to be measured. Since the spectroradiometric quantities in Clause 2 can often be related to each other if the measurement geometry is known (see 3.2.5), also different spectroradiometric quantities can sometimes be measured based on a single responsivity calibration, considering a single unit conversion factor.

A detailed description of calibration principles and methods for spectroradiometers is given in CIE 233:2019 (CIE 2019).

3.1.4 Direct substitution measurements

If in addition to the source to be measured (DUT) a reference source (ref) with known spectral distribution $X_{\lambda,\text{ref}}(\lambda)$ over the wavelength range of the DUT is available, spectroradiometric measurements of the DUT can be done without knowledge of the instrument responsivity $s(\lambda)$ by a so called direct substitution measurement, as long as $s(\lambda)$ is linear over the spectral bandpass around wavelength λ . A measurement of the reference source immediately before or after a measurement of the DUT directly relates the spectral distribution of the DUT to that of the reference source. Combining Equations (8) and (9) for $t \cong t_c$ gives

$$X_{\lambda,\text{DUT}}(\lambda) = \frac{Y_{\text{DUT}}(\lambda)}{Y_{\text{ref}}(\lambda)} \cdot X_{\lambda,\text{ref}}(\lambda) \quad (10)$$

where $Y_{\text{DUT}}(\lambda)$ and $Y_{\text{ref}}(\lambda)$ are detector signals of DUT and reference source, respectively.

Provided the spectral distributions of DUT and reference source are similar, direct substitution measurements often give the most accurate measurement results because they do not require long-term stability of the spectroradiometer responsivity and suppress most systematic measurement errors. If the reference source has a different spectral distribution than the DUT, systematic components of the effects discussed in Clause 4 will in general affect the measurement result.

A detailed description of responsivity calibration and direct substitution measurements using spectroradiometers is given in CIE 233:2019 (CIE 2019).

3.2 Measurands

3.2.1 General

The elementary measurement result of a spectroradiometric measurement is an estimate for the spectral distribution $X_{\lambda}(\lambda)$ of a radiometric quantity of an optical radiation source (see 2.6 to 2.9). Depending on the configuration of the measurement and the entrance optics of the spectroradiometer different quantities such as spectral irradiance, spectral radiance, spectral radiant intensity, spectral radiant flux, or their energy analogues (see 3.2.5) are determined over a limited spectral range. In many cases, the radiometric quantity X to be determined, is a function of one or multiple (weighted) integral(s) of the spectral distribution over a defined wavelength range. This leads to basic radiometric quantities such as irradiance, radiance, radiant intensity or radiant flux, spectrally weighted quantities like e.g. photometric quantities or spectral quotients like e.g. transmission and reflection.

3.2.2 Spectrally weighted quantities

When the effectiveness of optical radiation is of interest, so-called spectral weighting functions or action spectra, $A_{\text{act}}(\lambda)$, are introduced. An action spectrum represents the relative spectral effectiveness of optical radiation, for a specific actinic effect, in a specified system. The subscript “act” specifies the (actinic) effect. An action spectrum is dimensionless (of unit one) and if not stated otherwise, normalized to its maximum.

The associated effective radiometric quantity to an actinic effect is the spectral distribution weighted with the action spectrum:

$$X_{\text{act}} = K_{\text{act}} \int A_{\text{act}}(\lambda) \cdot X_{\lambda}(\lambda) d\lambda \quad (11)$$

where K_{act} is the actinic efficacy, which depends on the actinic function of interest, but in most cases is set to unity. If K_{act} is set to unity, the dimension of the effective radiometric quantity is the same as of the radiometric quantity causing the actinic effect.

An action spectrum usually describes an actinic effect of radiation on radiant sensitive surfaces or bodies like skin, human eye, retina, photosensitive material etc. It does not necessarily

describe a biological effect but can also represent other standardized functions such as the rectangular function of a radiometric interval (e.g. UV-A, UV-B, UV-C).

Examples for spectrally weighted quantities:

- Erythral Irradiance $E_{\text{er}} = \int A_{\text{er}}(\lambda) \cdot E_{\lambda}(\lambda) d\lambda$ where $A_{\text{er}}(\lambda) = s_{\text{er}}(\lambda)$ is the erythema spectral weighting function (ILV 17-26-067 (CIE 2020a)).
- Retinal thermal radiance $L_{\text{rth}} = \int_{380 \text{ nm}}^{1400 \text{ nm}} A_{\text{rth}}(\lambda) \cdot L_{\lambda}(\lambda) d\lambda$ where $A_{\text{rth}}(\lambda) = R(\lambda)$ is the retinal thermal hazard spectral weighting function (ILV 17-26-049 (CIE 2020a)).
- UV-B irradiance $E_{\text{UVB}} = \int_{280 \text{ nm}}^{315 \text{ nm}} A_{\text{UVB}}(\lambda) \cdot E_{\lambda}(\lambda) d\lambda$ where $A_{\text{UVB}}(\lambda) = 1$ between 280 nm and 315 nm and 0 elsewhere, representing the UV-B spectral range (ILV 17-21-008 (CIE 2020a)).
- Any photometric quantity, for example: Luminous flux $\Phi_{\text{v}} = K_{\text{m}} \int_{360 \text{ nm}}^{830 \text{ nm}} A_{\text{v}}(\lambda) \cdot \Phi_{\lambda}(\lambda) d\lambda$ where $A_{\text{v}}(\lambda) = V(\lambda)$ is the spectral luminous efficiency for photopic vision (ILV 17-21-035 (CIE 2020a)) and $K_{\text{m}} \approx 683 \text{ lm} \cdot \text{W}^{-1}$ is the maximum luminous efficacy for photopic vision (ILV 17-21-092 (CIE 2020a)).

Calculation of measurement uncertainties for spectrally weighted quantities requires information on the full covariance matrix of $X_{\lambda}(\lambda)$ since the individual values of $X_{\lambda}(\lambda)$ at different wavelengths λ are in general correlated to some degree and the degree of correlation can have significant effect on the measurement uncertainty. Details on the treatment of correlations in uncertainty calculations for spectral measurements are given in CIE 198-SP2:2018 (CIE 2018).

3.2.3 Spectral quotients

In some types of spectroradiometric measurements, two measured spectral distributions are compared wavelength by wavelength and the measurand depends only on the spectral quotient,

$R(\lambda)$, of two spectral distributions, $X_{\lambda,1}(\lambda)$ and $X_{\lambda,2}(\lambda)$: $R(\lambda) = \frac{X_{\lambda,1}(\lambda)}{X_{\lambda,2}(\lambda)}$. Measurements of spectral

quotients are in general dimensionless and do not necessarily require a responsivity calibration of the spectroradiometer used. If the compared spectral distributions are similar, systematic measurement errors for the two measurements can be highly correlated and their effect on the calculated ratio will therefore be significantly reduced. Examples for measurands expressed as spectral quotients are

- spectral transmission measurements, e.g. of optical filters;
- spectral reflection measurements, e.g. of optical mirrors;
- spectral absorption measurements, e.g. in analytical chemistry;
- spectral contrast measurements, e.g. of displays.

3.2.4 Energy analogues

The spectroradiometric quantities 2.6 to 2.9 all relate to the power in the unit watt (= joule per second) of the input signal. In some applications like dosimetry (e.g. measurement of exposure) or measurements of pulsed sources measurands related to the energy in the unit joule of the input signal are of interest. Since every measurement has a finite time resolution, correct timing of the measurement is important for accurate energy measurements.

For spectroradiometers using time-integrating detectors (like charge-coupled device (CCD) arrays), the signal of the calibrated detector is proportional to the energy (or photon flux) of the incident optical radiation. Average power is calculated by dividing the signal by the integration time and the energy signal can be easily recovered by multiplying the output signal by the

integration time. For the measurement of pulse energy (average pulse energy) of pulsed sources synchronization of the measurement with the repetition frequency of the source is important to ensure that a complete single pulse (or a known number of pulses) is detected within the set integration time.

For spectroradiometers using non-integrating detectors (like photodiodes), the output signal should be integrated over time to get an energy signal. Here, issues like temporal resolution (frequency response) of the detector and again synchronization with the source should be considered.

The role of timing in the measurement of time-varying input signals is discussed in more detail in 4.9.

3.2.5 Geometric relations

In situations where the spectral irradiance, $E_\lambda(\lambda)$, decreases proportional to the square of the distance, d , from the source in the direction of measurement (often called “far-field condition”), spectral irradiance and spectral radiant intensity have the simple relation

$$I_\lambda(\lambda) = \frac{d\Phi_\lambda(\lambda)}{d\Omega} = \frac{d\Phi_\lambda(\lambda)}{dA} \cdot d^2 = E_\lambda(\lambda) \cdot d^2, \quad (12)$$

which is the radiometric form of the photometric distance law (compare ILV entries 17-25-104, 17-25-105 (CIE 2020a)). The distance beyond which Equation (12) is fulfilled to within a given acceptable error is usually called the limiting photometric/radiometric distance (CIE 2013).

3.3 Input- and exit-optics

3.3.1 Input optics

3.3.1.1 General

The input optics of a spectroradiometer guide the optical radiation to be measured to the spectrally selective unit (SSU, see Annex A) of the spectroradiometer and ensure proper irradiation of the SSU. Different measurement geometries and/or quantities to be measured will in general require different types of input optics. The spectral responsivity and therefore the calibration of an instrument will be specific to the input optics used.

3.3.1.2 Apertures

Apertures (ILV 17-25-086 (CIE 2020a)) can be used to convert between different radiometric quantities and are therefore an integral part of most input optics. Knowledge of the dimensions of a planar aperture and the measurement geometry allows spectroradiometers to measure and convert

- average (spectral) irradiance over the area of the aperture – this requires either calibration with a(n) (spectral) irradiance standard or alternatively a (spectral) radiant flux standard and a known area of the aperture;
- (spectral) radiant flux – this requires uniform irradiation of the aperture and either calibration with a (spectral) radiant flux standard or alternatively a (spectral) irradiance standard and a known area of the aperture;
- average (spectral) radiant intensity over the solid angle defined by the aperture – this requires a distance to the optical radiation source much larger than the diameter of the aperture; Calibration can be performed by either a (spectral) radiant intensity standard or, alternatively, a (spectral) irradiance standard and a known distance to the source;
- average (spectral) radiance – an aperture can in principle also be used as the imaging element of a pinhole camera, which can be calibrated for (spectral) radiance.

For accurate conversions between radiometric quantities, it is important that the optically transmissive area of the aperture is very precisely defined and as accurately known as possible.

This requires very thin aperture edges (so-called knife edges) and a shape that can be geometrically measured as easily as possible. Proper positioning of apertures is also important (perpendicular to the beam path, sight-limiting, preventing diffraction, etc.).

Typically, the SSUs of spectroradiometers require uniform irradiation. Input optics with apertures as the element defining the measurement quantity will therefore in general feature additional optical elements to homogenize the radiation field transmitted through the aperture.

3.3.1.3 Diffusers

Diffusers are optical elements that transform a distribution of optical radiation that is non-uniform (with respect to irradiance and/or angle of incidence and/or polarization) at their input surface to a uniform distribution at their output surface (with respect to exitance and/or Lambertian radiance and/or polarization).

Diffusers are often used in input optics for irradiance, radiant flux and radiant intensity measurements for homogenizing and/or to achieve approximately a cosine response of the input optics with respect to the angles of incidence of the input radiation (here sometimes also non-planar diffuser geometries are used).

Most diffusers are based on (pseudo-random) scattering of optical radiation by diffuse reflection from a rough surface or transmission through a medium of highly non-uniform refractive index (for example a piece of glass with enclosed air bubbles). The uniformity of the radiation field at the output surface of the diffuser depends on the size and density of the scattering centres compared to the irradiated area at the input surface and the number of scattering events along the optical path to the output surface. For most diffusers, the total transmission decreases with increasing uniformity at the output of the diffuser.

Common diffuser materials include ground or sand-blasted quartz, polytetrafluoroethylene (PTFE), sintered glass and opal glass.

Several different materials are suited for specific wavelength ranges. Especially for transmissive diffusers thickness is important in determining the scattering properties, which in turn determine the cosine response of the diffuser, but thickness can also limit the usable spectral range of a diffuser. Thinner materials generally have weaker scattering and poorer cosine match, but transmit more optical radiation. Generally, the properties of a transmissive diffuser represent a compromise between good cosine adaption and high transmittance. Scattering depends on wavelength and is much stronger at short wavelengths. Thus, a diffuser can only be optimized over a certain wavelength range. Typically, at shorter wavelengths the transmittance drops and at longer wavelengths the cosine matching degrades.

Sand-blasted quartz transmits over a wide spectral range but generally only scatters sufficiently at very short wavelengths, e.g. 200 nm to 250 nm. PTFE has stronger scattering and can be used starting from 200 nm to 400 nm, though thicker diffusers can move the range up to the infrared. Opal diffusers absorb ultraviolet (UV) wavelengths but are excellent for visible and near infrared wavelengths when sufficiently thick.

Reflective diffusers are either corrugated reflective surfaces or often made from the same materials as transmissive diffusers but sufficiently thick, so that optical radiation is mostly reflected rather than transmitted. They are usually irradiated perpendicular to their surface and the reflected radiation in a specified direction (usually 45°) is imaged onto the SSU of the spectroradiometer. Reflective diffusers are less common owing to the inherently larger space requirements.

Microstructured diffractive diffusers allow to tailor the diffusion (or many other optical wavefront modifications) using only a very thin layer of material and with high total transmittance. Their application is typically limited to a relatively small wavelength range around a given design wavelength.

For all types of diffusers the relevant input surface as reference plane for radiometric measurements should be determined. It might be possible that this surface is within the diffuser itself, especially in the long wavelength range, as long-wavelength radiation first enters the

diffuser before it is reflected inside, whereas short-wavelength radiation is reflected right at the surface of the diffuser. Thus, the reference plane could be wavelength-dependent. If the thickness of the diffuser is small in order to increase transmittance, it might be, that the reference point is located behind the diffuser or no reference plane for irradiance can be defined. A limiting aperture in front of the diffuser can solve this problem.

Figure 1 shows different working principles of common types of diffusers.

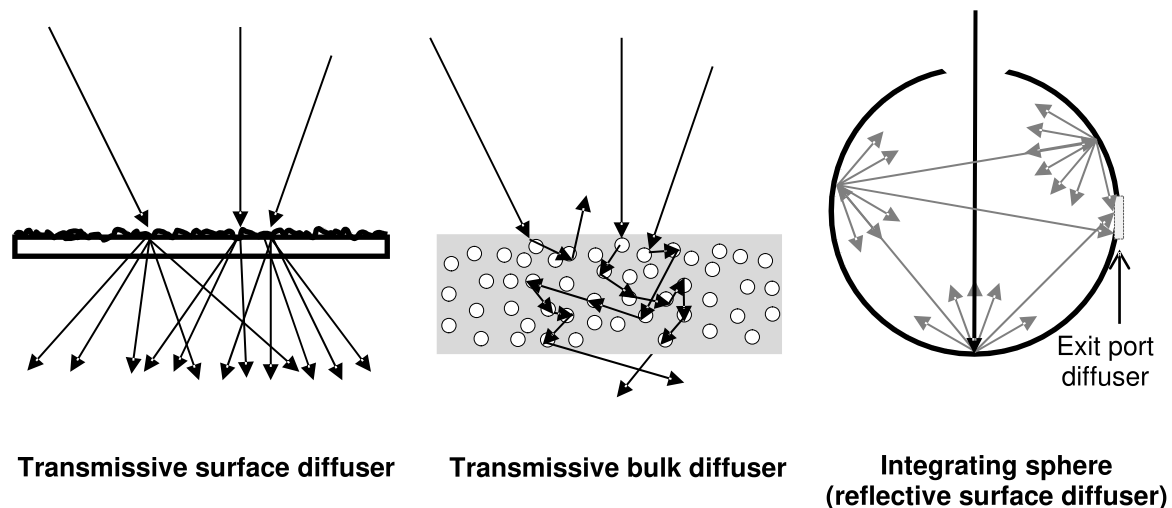


Figure 1 — Illustration of the working principles of common types of diffusers

3.3.1.4 Integrating spheres

An integrating sphere is a hollow, diffusely reflecting enclosure (not necessarily a sphere) with at least two openings. Radiation can enter the sphere through one port, radiation leaving the sphere through the second port is guided to the SSU of the spectroradiometer. For systems where the source is placed inside the sphere, there is usually only a detection port, but the sphere can be “opened” to mount the source and closed again before measurement.

Integrating spheres can be regarded as a special type of diffuser (see 3.3.1.3). Through multiple diffuse reflections at the sphere wall a very uniform irradiance distribution across the wall of the sphere is achieved, independent from the radiance distribution at the input port. Compared to other diffuser geometries, integrating spheres often have a larger acceptance angle (close to 2π if the source is placed at the entrance port or close to 4π for a source placed in the centre of the sphere), can have better cosine response and often also have better uniformity of the output. Because the transmittance of the sphere scales with the ratio of detector port area to sphere surface area, transmittance of integrating spheres is in general small compared to other input optics. For best performance the detection port is usually covered by an additional transmissive diffuser placed at the sphere surface and the port is shielded against direct irradiation through the measurement port, so that radiation from all angles of incidence (i.e. every other point on the sphere) will contribute approximately equally to the detected signal.

Performance of integrating spheres is best if the combined areas of entrance and detection port are small compared to the sphere's inner surface area and the reflectance of the sphere wall is high, spectrally uniform and diffuse. Uniformity and total transmittance increase with reflectance for a given geometry (see CIE 233:2019 (CIE 2019) for more details).

The most common surface materials used for integrating spheres are barium sulphate (BaSO_4) and polytetrafluorethylene (PTFE). Both materials allow sphere coatings with a reflectance well above 90 % from ultraviolet (UV) to infrared (IR) wavelengths. For applications sensitive to fluorescence (typically measurements of UV sources) and in the IR also metallic coatings (e.g. gold, aluminum) on sandblasted sphere surfaces are used.

Because of the properties outlined above, integrating spheres are most often used in measurements of spectral radiant flux (due to their large acceptance angle) or spectral irradiance (due to their potentially good cosine response).

3.3.1.5 Imaging optics

Imaging optics are used for spectral radiance measurements as they transfer radiation emitted from a surface area into the field of view (ILV 17-25-077 (CIE 2020a)) of the imaging system. The field of view is determined by the size of the entrance pupil of the imaging system and the distance to a detector. Imaging optics therefore are well suited for measuring average radiant flux per area and solid angle. Depending on the application, either a diffuser or an optical fibre (or other optical radiation guide) with a core diameter covering the full or part of the field of view is placed in the image plane. In any case, the lateral information about the radiance distribution of the source is in general not transferred to the spectroradiometer (with the exception of hyperspectral cameras), but can be reconstructed from multiple measurements imaging different parts of the source surface.

Figure 2 shows a typical setup of imaging input optics.

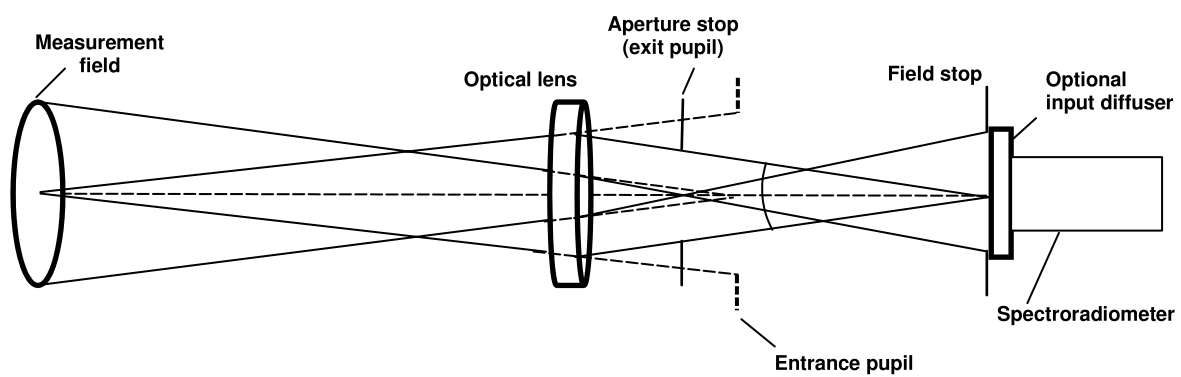


Figure 2 — Typical setup of imaging input optics

3.3.2 Exit optics

The use of output optics depends on the design of the spectroradiometer. In the case of an array spectroradiometer there is typically no exit slit, and its array detector together with any required spectral filters (e.g. order sorting filters) is placed at the location of the dispersed image of its entrance slit. For a mechanically-scanning spectroradiometer, a single element detector may be directly placed near the exit slit so that no output optic is needed. If the single element detector is too small compared to the exit slit (which is often the case for an infrared or near-infrared spectroradiometer) or there is not enough space to mount the detector near the exit slit, an output optic is needed for imaging the exit slit to the detector. The aperture size of the output optic should be large enough to collect all optical radiation from the exit slit (i.e. underfilling the aperture), and the magnification of the output optic should be as small as possible so that a smaller detector can be used, which improves the performance of the detector (such as lower noise, higher shunt resistance, etc.). Both lenses and spherical (or aspherical) mirrors can be used as the output optic. A lens output optic tends to be more compact while a mirror output optic can cover a wide spectral range. A mirror output optic also does not have any chromatic aberration and its astigmatism aberration can be corrected (Liu and Yu 2012). The exit slit or image of the exit slit should underfill the detector to reduce the sensitivity of the spectroradiometer to ambient temperature because the irradiance on the exit slit is normally highly non-uniform.

3.4 Measurement geometries

3.4.1 General

The definitions of the spectroradiometric quantities in Clause 2 set requirements on the type of input optics (see 3.2.4) and measurement geometries used for their measurement.

3.4.2 Irradiance

Irradiance, E_e , is defined as the density of incident radiant flux, Φ_e , with respect to area, A , at a point on a real or imaginary surface: $E_e = \frac{d\Phi_e}{dA}$ (ILV 17-21-053 (CIE 2020a)). Real irradiance detectors will always measure average irradiance over their finite radiation sensitive area. For a uniform irradiance distribution across the detector area, the measured average irradiance will correspond exactly to the differential irradiance definition according to the ILV. For a non-uniform irradiance distribution, the measured average irradiance will contain no information about the distribution of irradiance across the detector, which can lead to misleading measurement results. As an example, for a uniform, collimated radiation beam with radiant flux, Φ_e , and a beam diameter smaller than the acceptance area of the detector, the measured irradiance will be independent of the beam diameter, d , while the true irradiance will be proportional to $1/d^2$. Good irradiance measurements therefore require uniform irradiation of the detector area. In practice, this will often set requirements for either the area for the detector, the distance to the source, or both.

The area of the detector projected along the direction of incidence of the optical radiation is proportional to the cosine of the angle, θ , between the surface normal of the detector and the direction of incidence of the detected radiation. A detector will therefore measure irradiance correctly, independent of the angle of incidence, only if its responsivity also varies with the angle of incidence as $\cos \theta$, such that the two cosine factors cancel in the determination of irradiance ($E_e(\theta) = \frac{d\Phi_e}{dA \cdot \cos \theta} \cdot \cos \theta = \text{const.}$), in which case the detector is said to have good “cosine response” or good “cosine adaption” (see also 3.3).

For a non-uniform irradiance distribution on the (not necessarily planar) surface of observation, the measured irradiance values will in general be specific to the position and/or orientation of the detector and the irradiance distribution can be reconstructed from multiple measurements taken at different detector positions on the surface of observation.

3.4.3 Radiant intensity

Radiant intensity, I_e , is defined as the density of radiant flux, Φ_e , with respect to solid angle in a specified direction, Ω : $I_e = \frac{d\Phi_e}{d\Omega}$ (ILV 17-21-044 (CIE 2020a)). Real radiant intensity detectors will always measure average radiant intensity over a finite acceptance angle (the field of view, as defined in the ILV (CIE 2020a), entry 17-25-077) and with respect to a finite area on the radiant surface of the source. Analogous to irradiance measurements discussed above, good radiant intensity measurements require uniform irradiation over the acceptance angle of the detector. In addition, the definition of radiant intensity requires that the source can be regarded to be a point source, as otherwise radiation emitted from different points on the surface of the source into different directions will be detected simultaneously and incorrectly assigned to the same direction of observation. In practice, this requirement is often fulfilled if the distance from the detector to the source is much larger than the largest dimension of the source surface as well as the detector area (see 3.2.5).

The radiant intensity distribution of a source can be measured with a goniometric setup, where either the source is rotated around its optical radiation centre or a radiant intensity detector is moved on a spherical trajectory around the source (CIE 239:2020 (CIE 2020b)).

If the source can be regarded as a point source and the distance to the source d as well as the area A of the radiation sensitive area of the detector are known, radiant intensity measurement results can be converted to irradiance values and vice versa via the approximate relation between solid angle, Ω , and area: $\Omega \cdot d^2 \cong A$ (see also 3.2.5).

3.4.4 Radiant flux

A radiant flux measurement in general requires detection of all radiation emitted by a source and is most often done by either integration of a goniometric measurement of the radiant

intensity distribution over all angles (see 3.4.3) or by collecting the emitted radiation with an integrating sphere (see 3.3.1.4). Sometimes “partial” radiant flux measurements are performed where the radiant flux emitted into a limited solid angle or incident on a given surface is calculated from a radiant intensity or irradiance measurement, respectively.

For goniometric measurements, detectors are usually calibrated either for radiant intensity or for irradiance (with subsequent conversion of the measurement results to radiant intensity using Equation (12), see 3.2.5 and 3.4.3). Integrating sphere detectors are usually calibrated directly for radiant flux as the properties defining their responsivity are most often too complex to allow accurate conversion of e.g. an irradiance measurement result to radiant flux.

3.4.5 Radiance

Radiance is defined as the density of radiant intensity, I_e , with respect to projected area, $A \cdot \cos \alpha$, in a specified direction at a specified point on a real or imaginary surface (ILV 17-21-049 (CIE 2020a)). Radiant intensity, radiant flux and the irradiance distribution produced by the source on a given surface, can all be calculated from the radiance distribution on the source surface.

Radiance is most often measured using imaging optics (see 3.3.1.5). Real radiance measurements measure radiance averaged over the field of view and with respect to a finite area (fundamentally limited by the properties of the imaging optics, e.g. expressed by the point spread function for spatially resolving detectors like in hyperspectral cameras) in the plane of the source.

A measurement of the radiance distribution of a source requires either several measurements with a field of view that is small compared to the source area and an acceptance angle that is much smaller than 2π , or a goniometric measurement with a (hyperspectral) camera.

3.5 Standard lamps

3.5.1 General

A lamp source chosen for use as a spectroradiometer responsivity calibration standard should fulfil a number of requirements, as detailed in 3.5.2 to 3.5.4 below (see also 3.1.3). The best choice of standard lamps for any given situation will depend on balancing the relative importance of each of these requirements, taking into account the properties of the spectroradiometer, the application(s) for which the spectroradiometer is intended to be used, and the targeted measurement uncertainty. In addition, the chosen standard should be calibrated in terms of the measurand that is appropriate for the spectroradiometer input optic geometry (i.e. radiance calibration for radiance input optics, irradiance calibration for irradiance input optics, see 3.2.4 and 3.4), and the calibration should be traceable to a national metrology institute (NMI) or accredited (e.g. ISO 17025) metrological laboratory to ensure linkage to the SI system of units (BIPM 2019). Ideally at least two reference standards should be used, since this allows comparison between them and can help with early identification of any issues.

3.5.2 Spectral coverage

It is essential that the spectroradiometer can be calibrated over its full spectral operating range. For a spectroradiometer with wide spectral coverage (e.g. UV to IR) this may necessitate the use of more than one calibration standard, and in this case some spectral overlap between the different standards is recommended. In addition, it is desirable for the chosen reference source to provide a smoothly-varying spectral distribution over the wavelength range for which it is used, without any narrow emission peaks or absorption bands. Any regions where the emission characteristics change rapidly with wavelength can lead to large measurement errors when the spectroradiometer is subsequently used to measure test sources with a very different spectral distribution, due to errors in the wavelength scale.

The requirements for broad spectral coverage and smooth spectral power distribution are often met by using tungsten filament / quartz halogen lamps operated in DC mode. When these are run at high correlated colour temperatures they can be used to cover the spectral region from 250 nm to 2 500 nm (see Figure 3). The sources most frequently employed by NMIs are

1 000 W FEL¹ lamps, while for compact setups with array spectroradiometers, 250 W quartz halogen projector lamps are often used. Deuterium lamps are typically used for shorter UV wavelengths, below about 380 nm (see Figure 3); their use at longer wavelengths is compromised due to the presence of narrow emission lines.

Although tungsten lamps are generally the most versatile standard sources, offering broad spectral coverage and no emission lines, their availability is becoming increasingly limited. Other sources are therefore becoming more common, particularly in the visible spectral region where LEDs are now widely used. Although these have a less-smooth spectral distribution than tungsten filament lamps and a very limited spectral range, the peaks and troughs in their emission are generally quite broad. This means that measurement errors due to errors in the spectroradiometer wavelength scale are typically relatively small and, in most cases, can be allowed for in the uncertainty budget rather than requiring corrections to be applied.

In situations where the spectroradiometer is intended to be used to measure a source which has narrow spectral features, such as high-pressure discharge lamps, the use of a calibration reference with similar spectral characteristics can minimize wavelength-related errors and lead to a lower overall measurement uncertainty. This direct substitution approach (see 3.1.4) is often used where the spectroradiometer is to be used for measurements of only a limited range of sources, such as in some quality control testing applications.

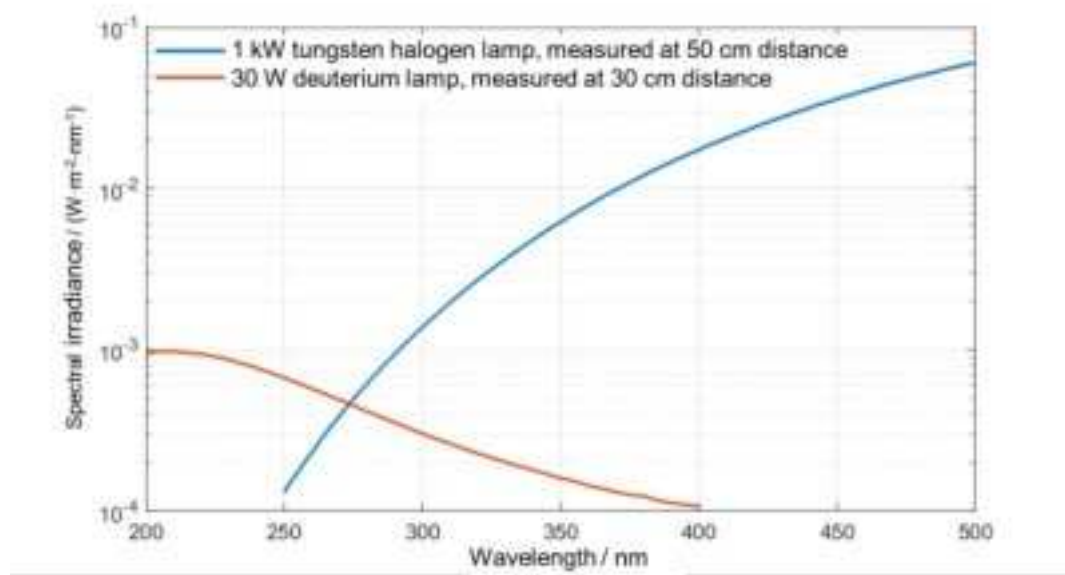


Figure 3 — Spectral characteristics of 1 000 W tungsten halogen and 30 W deuterium discharge lamps

Calibration using a source with similar spectral characteristics as the test source is also advantageous in cases where internal heterochromatic stray light is present, since this will minimize the associated stray light errors and uncertainties (see 4.7.1.3).

Whichever type of source is used, it is important to take into account that the electrical operating conditions have a significant impact on the output of the source, and will change not only its absolute level, but also its shape of the spectral distribution (see 4.19.2). In the case of a tungsten filament lamp operating at about 3 000 K, for example, changing the operating current by 0,10 % leads to a change of about 1,5 K in the correlated colour temperature and changes in the absolute spectral irradiance of nearly 1 % at 250 nm, about 0,5 % at 450 nm, about 0,2 % at 1 200 nm and about 0,1 % at 2 500 nm. It is therefore necessary to reproduce and control

¹ FEL is an American National Standards Institute (ANSI) standard designation for a 1 000 W tungsten-halogen lamp with a G9.5 medium 2-pin base.

the electrical operating conditions with a high degree of precision if reliable results are to be obtained.

Environmental conditions can also have a large influence on the spectral distribution. For example, discharge lamps, deuterium lamps and LEDs are very sensitive to air currents and temperature changes. It is therefore necessary to either thermostat these sources or monitor and control ambient temperature and protect the sources from draughts.

Since the spectral sampling of standard lamp reference spectra in general will not match the spectral sampling of the spectroradiometer to be calibrated, interpolation of standard lamp spectra will usually be necessary. Guidance on appropriate interpolation of standard lamp spectra can be found in CIE 233:2019 (CIE 2019).

3.5.3 Geometrical characteristics

The geometry of the input optics for the spectroradiometer (see 3.4) has a very strong influence on the choice of the most appropriate calibration standard.

In the case of irradiance (or radiant intensity), it is important that the calibration standard can be set up in exactly the same way with respect to the spectroradiometer input optics each time it is used. To meet this requirement, irradiance calibration standards are typically designed to have a planar front window (or other planar reference surface, see e.g. Figure 4) which can be set perpendicular to the optical axis of the spectroradiometer, or are used with an alignment jig that can be used to set the orientation (see Figure 4). In addition, it should be constructed such that the calibration distance can be measured precisely from a reference point on the lamp, the lamp enclosure, or the lamp mount. It is, however, not essential for an irradiance reference standard to obey the inverse square law if it is always used at the distance at which it was calibrated. Distance is generally measured from the front of the lamp housing or mount or from the window or alignment jig, as appropriate. In all cases, the calibration certificate for the reference standard should give precise details of the alignment and distance used for the calibration, and these conditions should be reproduced during subsequent use.

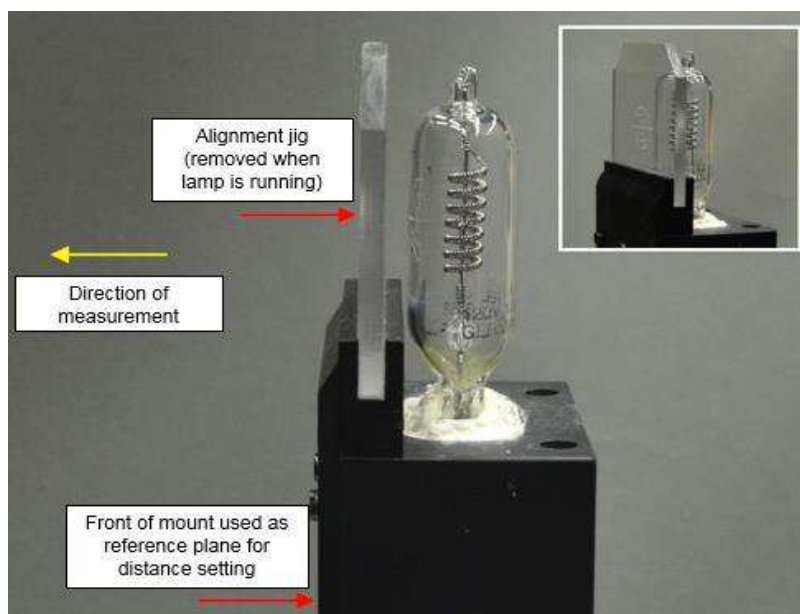


Figure 4 — 1 000 W FEL quartz halogen lamp with alignment jig

The intensity distribution of a source to be used as a standard of irradiance or radiant intensity should be uniform, preferably to better than $\pm 0,25\%$, over the irradiated area or angle. In the case of tungsten filament lamps, coiled filaments, especially single coils arranged in a regular pattern, can show rapid changes of intensity with angle of view as the front turns of the filament mask the rear turns to a greater or lesser extent. Uniformity is improved if the lamp envelope is diffusing, but if clear, it should be of good optical quality. Lamps are often grit blasted to achieve more uniform irradiance, but the surface is then vulnerable to contamination and consequent

discoloration. Furthermore, where a lamp has a diffusing envelope, it is almost impossible to define the position of the optical radiation centre. Similar uniformity considerations apply for other types of calibration reference, such as multi-element LED sources; again diffusers are often used to improve performance in this respect.

Reference sources for radiance measurements are usually designed to provide uniform radiance, i.e. a closely-Lambertian distribution with emission angle and good spatial uniformity of emission over the radiating area. In this case the radiance is reasonably insensitive to changes in the size, shape, location and angular extent of the imaged area and as a result the imaging geometry of the spectroradiometer has only small influence on the measurement result and the associated measurement uncertainties will therefore be small as well. Two approaches for practical realization of uniform radiance sources are widely used: an irradiance source plus reflective diffuser (Figure 5) or a 'radiance gauge' consisting of a small source coupled to an integrating sphere (see Figure 6 for an example). For an integrating sphere, the irradiance distribution is approximately uniform over the sphere's inner surface, leading to good lateral uniformity of the radiation emitted through the exit port. The projection of the exit port area onto the direction θ from the centre of the exit port to any point on the sphere's inner surface decreases proportional to $\cos \theta$, leading to an approximately Lambertian distribution of emission angles. In cases where the spectral characteristics of LEDs make them suitable standards, an LED array may be suitable, but in this case it is important to use a suitable diffuser to improve the spatial and angular uniformity; direct imaging of the LED array using the spectroradiometer can lead to large calibration errors.

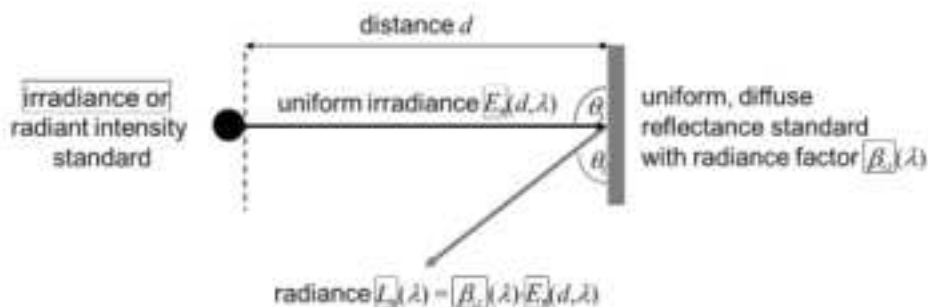


Figure 5 — Radiance standard comprising irradiance or radiant intensity standard and reflecting diffuser

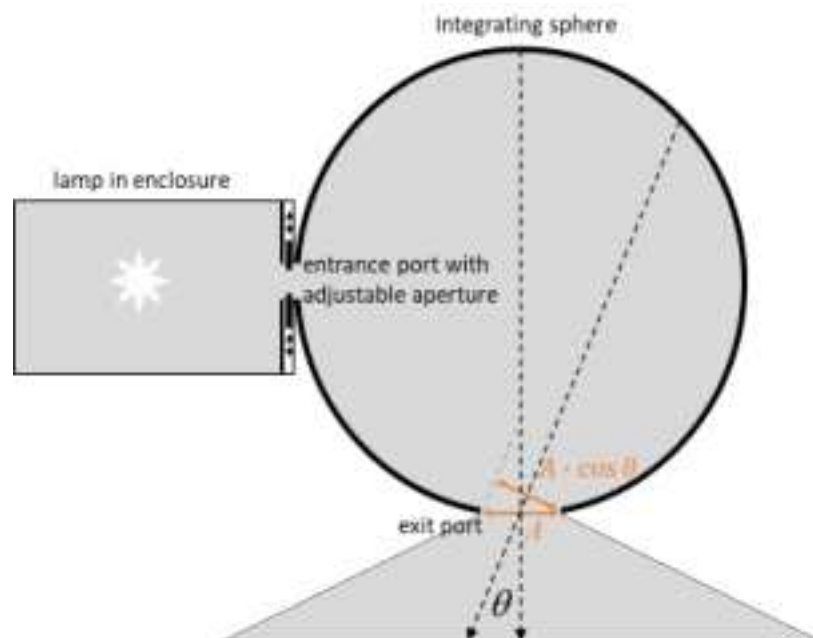


Figure 6 — Radiance gauge reference standard

Whatever type of radiance source is chosen, the reference direction and alignment method, the location and size of the calibrated area, and the solid angle subtended by the optical system of the detector, should all be specified and the impact of any departures from these conditions during subsequent use should be allowed for in the uncertainty budget.

3.5.4 Stability

A key requirement for any calibration reference standard is that it should provide closely the same output quantity each time it is used. Good control of the electrical operating conditions, coupled with the alignment features mentioned in 3.5.3, will go some way towards ensuring this, but it is also essential that any changes over time are relatively small. Many sources used as radiance and irradiance calibration standards show a gradual change in output each time they are used. This is particularly true in the case of tungsten filament / quartz halogen lamps. The rate of change, and the resultant measurement uncertainty, determine the calibration lifetime i.e. the time for which the source can be used before it should be recalibrated. It is also important to remember that the ageing rate varies significantly with wavelength. Tungsten filament / quartz halogen lamps, for example, show much more rapid changes in spectral output with use at wavelengths in the UV region than in the visible or NIR regions. It is important to evaluate the ageing rate for any source that is used as a calibration reference standard, and to allow for this in the uncertainty budget (see 4.19.2).

Some sources can show changes in output even when they are not used, or demonstrate ageing characteristics that depend on the number of times they are switched on and off rather than the total time for which they have been operated. Studies of long-term stability should include consideration of these possible effects and they should be allowed for in the associated uncertainty evaluation.

Short-term noise effects also need to be considered when choosing the most appropriate reference standard for calibration purposes. Although it is often possible to reduce the impact of noise by integrating the readings over a period of several seconds or even tens of seconds, there are situations where this is not desirable or possible. For example, there may be a maximum integration time in the case of an array-based spectroradiometer, while for a scanning monochromator system a long integration time at each wavelength can lead to unacceptably long measurement times. Inherently noisy sources, such as discharge lamps, are generally best avoided unless other considerations take priority, such as wavelength coverage or a desire to use a calibration source with characteristics similar to the anticipated test sources.

4 Measurement uncertainty contributions

4.1 General

The determination of measurement uncertainties is an essential part of the evaluation of measurements. In the following, the most important measurement uncertainty contributions are named and their possible influence on spectroradiometric measurements is specified. Guidance for the establishment of measurement uncertainties are given in JCGM 100:2008: Evaluation of measurement data – Guide to the expression of uncertainty in measurement (JCGM2008, abbreviated as GUM in the following) and its supplements. More specific guidance for spectroradiometric measurements is given in CIE 198-SP1.2 (CIE 2011) and CIE 198-SP2:2018 (CIE 2018). Statements relating to measurement uncertainties are formulated in (JCGM 2008).

4.2 Wavelength scale

4.2.1 Definition

A spectroradiometer maps the spectrum $X_\lambda(\lambda)$ of the optical radiation at its input to an electrical signal amplitude $Y(\lambda)$ (see also 3.1.2). The wavelength uncertainty $u(\lambda)$ has two contributions: a constant offset to the nominal wavelength λ_0 and a random deviation caused e.g. by the mechanical variations of the spectroradiometer.

4.2.2 Effect on radiometric quantity measured values

The uncertainty of the wavelength setting can have a significant effect on the measured spectrum wherever the spectrum changes significantly with wavelength.

The correct wavelength setting is especially important in measurements of narrow spectral features where it can have a significant effect on measurements of the spectral shape and position of spectral features. The effect on spectrally integrated quantities like total (or partial) radiant flux or averaged LED spectral radiant intensity (CIE 2007) also depends on the variation of the wavelength setting. If the wavelength setting varies only little with wavelength, its effect on the integral is small. For the limiting case of constant wavelength offset, corresponding to a global wavelength shift of the spectrum, no effect on the integral over the spectrum can be seen unless the integral is taken only over part of the spectrum. If the deviation to the nominal wavelength varies randomly over the measured spectrum and the spectrum has no dominant narrow features, the effect on the radiometric integral asymptotically approaches that for a constant offset for high sampling rates.

The wavelength setting is sensitive to any other effect affecting the shape of the spectrum (bandpass, stray light, fluorescence, higher order or double diffraction, etc.).

Common sources of wavelength uncertainty contributions are changes in the optical path within the instrument due to mechanical misalignment induced by e.g. vibration and shock, ageing of materials or differential thermal expansion of materials.

4.2.3 Quantifying the effect

A direct quantification of the sensitivity of measured radiometric quantities on uncertainties in the wavelength scale is in general not feasible.

The wavelength uncertainty can be estimated from the statistics of a series of repeated wavelength scale calibrations as described in 3.1.2. It usually also has systematic contributions from changes in temperature and any other effect that affects the optical path within the instrument. Those effects should be quantified separately by e.g. climate chamber or vibration/shock measurements.

Uncertainties in the calibration of the wavelength scale can be determined experimentally by measurements of additional reference lines not used for calibration. In cases where the parameters of the interpolation for the wavelength scale are determined from a fit to the calibration measurement, a statistical analysis of the goodness of fit and the residuals can be used to estimate uncertainties in the wavelength scale.

4.2.4 Correction of results

Deviations from the nominal wavelength setting should be minimized by proper calibration of the wavelength scale. Measures to ensure good wavelength calibration include:

- Careful selection of calibration reference sources: narrow (bandpass-limited) spectral features, no more than one spectral feature within the instrument bandpass, accurately known peak wavelengths, insensitive to expected variations in measurement conditions (temperature, humidity, source operation, etc.).
- Sufficient number and even distribution of reference lines: Ideally, reference lines should be approximately evenly distributed over the wavelength range of the instrument. The number of lines should be sufficiently large for accurate interpolation, e.g. if a polynomial of order n is used for interpolation, a minimum of $2n$ reference points should be used.
- Choice and validation of an appropriate interpolation method based preferably on a physical understanding of the instrument. If number and spacing of calibration lines are such that the wavelength scale is to good approximation linear between reference points, linear interpolation between calibration points can be sufficient.
- The signal-to-noise ratio in the calibration measurements should be sufficiently high, so that random measurement noise has no significant effect on the measurement result.
- Reference wavelength values should be assigned to the centroids of the measured signals for the reference lines, as the centroid position is not affected by the bandpass of the instrument (other than for example the peak wavelength).

For scanning instruments a good mechanical design of all moving parts is important to ensure a small position uncertainty.

4.2.5 Treatment of measurement uncertainties

The uncertainties $u(\lambda)$ at different wavelengths are in general strongly correlated via the interpolation model for the wavelength scale and the working principle of the instrument. The estimation of uncertainties for quantities depending on values of the spectrum at multiple wavelengths therefore should account for the covariance matrix $u^2(\lambda, \lambda')$ of the wavelengths.

The wavelength scales of scanning spectroradiometers are usually to good approximation linear in the scanning variable. If the uncertainties of the reference wavelengths, $u(\lambda_i)$, are normally distributed and uncorrelated, which is often the case, the uncertainties, $u(\lambda)$, are normally distributed and uncorrelated as well and the standard GUM procedure for the propagation of uncertainties, neglecting off-diagonal elements of the covariance matrix, can be applied. For array spectroradiometers, the wavelength scale is typically non-linear and therefore the uncertainties, $u(\lambda)$, will be correlated and no longer be normally distributed. In this case a full covariance analysis should be done unless the contributions of the deviation from a normal distribution and of the covariance to $u(\lambda)$ are small with respect to the desired precision of the uncertainty calculation.

Since the sensitivity coefficient of the uncertainty in the spectrum for wavelength error is the first partial derivative of the spectrum with respect to wavelength, the contribution of wavelength uncertainties to the uncertainty of spectroradiometric measurements is correlated with any other contribution affecting the signal amplitude.

When uncertainties are estimated by Monte Carlo methods, the distributions and correlations of the reference wavelengths $\{\lambda_i\}$ and the interpolation model are needed as inputs to determine the wavelength uncertainties.

4.3 Bandpass and sampling

4.3.1 General

The result of a spectroradiometric measurement is a reconstruction of the measured spectrum from a finite set of detector signals at the output of a spectroradiometer. Bandpass and sampling describe the effects of finite spectral resolution and finite number of detector values in any real spectroradiometric measurement on the measurement result.

A detailed discussion of the effects of bandpass and sampling on spectral measurements is given in CIE 214:2014 (CIE 2014).

4.3.2 Definition

4.3.2.1 Bandpass

The system bandpass describes how a spectral distribution is distorted by the system that is measuring it. Generally speaking, the components and geometrical arrangement of the spectroradiometer will “broaden” a spectral feature. The effect can be seen through the measurement of an emission line of a low-pressure discharge source (similar to the principle of applying a delta function or unit impulse function to a sampling system). Widening the slits may increase the amount of signal measured, but it also broadens the system bandpass.

For scanning spectroradiometers (monochromators) with a long focal length and rectangular slits the bandpass is normally a symmetrical triangular shape (representing the convolution of two rectangles). For array spectroradiometers the bandpass is more like a Gaussian shape but can be strongly asymmetrical particularly towards the edges of the available wavelength range.

The bandpass function $B(\lambda) = b(\lambda - \lambda_0)$ describes the dispersion of the detector readings $Y(\lambda)$ due to the finite spectral resolution of the instrument (see CIE 214:2014 (CIE 2014)):

$$Y(\lambda) = s(\lambda) \cdot (X_\lambda * B)(\lambda) = s(\lambda) \cdot \int_{\lambda - \Delta_l}^{\lambda + \Delta_u} X_\lambda(\lambda') \cdot b(\lambda' - \lambda) d\lambda' \quad (13)$$