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TECHNICAL REPORT

Characterization and Calibration Methods of UV Radiometers

CIE 220:2016

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535.31

Descriptor: Spectrophotometry
Ultraviolet rays

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Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen berichtet und überprüft werden, sowie neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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This Technical Report has been prepared by CIE Technical Committee 2-47 of Division 2 "Physical Measurement of Light and Radiation" and has been approved by the Board of Administration as well as by Division 2 of the Commission Internationale de l'Eclairage for study and application. 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 CIE 2-47 de la 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, pour étude et emploi. 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 CIE 2-47 der 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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CONTENTS

Summary	V
Résumé	V
Zusammenfassung	V
1 Introduction	1
1.1 Objectives	1
1.2 Scope	1
2 Definitions (General)	1
3 Quality indices	5
4 Properties of UV radiometers	7
4.1 Initial adjustment	7
4.2 Effective responsivity against a reference-spectrum source	8
4.3 Spectral matching	9
4.4 Short- and long-wavelength range response characteristic	10
4.5 Directional response	11
4.6 Linearity	13
4.7 Display unit	13
4.8 Fatigue	14
4.9 Temperature dependence	15
4.10 Humidity resistance	16
4.11 Modulated radiation	17
4.12 Polarization	18
4.13 Spatial non-uniformity response	19
4.14 Range change	20
5 Specification of UV radiometers	21
6 Calibration of UV radiometers	22
6.1 Mathematical description for the determination of responsivity in terms of weighted irradiance	22
6.2 Source-based approach	23
6.3 Detector-based approach	24
6.4 Full calibration method	26
6.4.1 Procedure for the measurement of the spectral irradiance responsivity	26
6.4.2 Procedure for the measurement of spectral irradiance and spectral distribution of the source	27
6.4.3 Procedure for the calibration of the effective irradiance responsivity of UV radiometers	28
6.5 Detector-based secondary calibration method by direct comparison	28
6.5.1 Procedures using detector standards	29
6.5.2 Procedures using source standards	29
6.6 Performance requirements for reference UV radiometers	29
6.7 Calibration interval for UV radiometers	31
7 Uncertainty evaluation	31
7.1 Method	31
7.2 Major sources of uncertainty	31
Annex A	33
A.1 Reference-spectrum sources for broad-band characterization	33
A.2 Linearity of UV radiometers	45
References	45

CHARACTERIZATION AND CALIBRATION METHODS OF UV RADIOMETERS

Summary

This technical document prepared by CIE Technical Committee TC 2-47 describes quality indices for UV radiometers, which are helpful for manufacturers and users to characterize instruments on a common basis. To harmonize CIE documents, the quality indices described in this document relate to the quality indices described in Joint ISO/CIE International Standard ISO/CIE 19476:2014(E) (formerly CIE S 023/E:2013), and references are made to those where applicable.

Different from photometers, the subject of ISO/CIE 19476:2014(E), UV radiometers may be designed for various actinic spectra and different spectral ranges. Therefore, instead of only one defined reference-spectrum source (CIE Source A) used in ISO/CIE 19476:2014(E) three reference-spectrum sources are proposed in this document to support the generic spectral characterization of UV radiometers for various applications. The defined spectra of reference sources for the characterization of UV radiometers are given in Annex A.

This document also describes source-based and detector-based methods along with measurement conditions and limiting boundary conditions for the calibration of UV radiometers used for laboratory as well as industrial applications.

CARACTÉRISATION ET MÉTHODES D'ÉTALONNAGE DE RADIOMÈTRES UV

Résumé

Ce rapport technique, utile autant aux fabricants qu'aux utilisateurs, a été élaboré par le comité technique TC 2-47 de la CIE et décrit, sur une base commune, les caractéristiques des radiomètres UV. Afin d'harmoniser les documents de la CIE, les caractéristiques décrites dans le présent document se rapportent à la norme internationale commune ISO/CIE 19476:2014(E) (anciennement CIE S 023/E:2013) à laquelle il est fait référence à chaque fois qu'elle est applicable.

Contrairement aux photomètres qui eux sont décrits dans la norme ISO/CIE 19476:2014(E), les radiomètres UV peuvent être conçus pour différents spectres actiniques et différentes étendues spectrales. Plutôt que d'utiliser la seule source de spectre de référence (illuminant A de la CIE) définie, le présent rapport propose trois sources de spectre de référence afin de contribuer à la caractérisation spectrale générale des radiomètres UV pour diverses applications. Les spectres de référence définis pour la caractérisation de radiomètres UV sont listés dans l'annexe ci-jointe.

Le présent rapport décrit en outre des procédés reposant d'une part sur le récepteur, d'autre part sur l'émetteur de rayonnement, ainsi que les conditions de mesures et les conditions secondaires restrictives pour l'étalonnage de radiomètres UV utilisés en laboratoire ou dans des applications industrielles.

CHARAKTERISIERUNG UND KALIBRIERMETHODEN VON UV-RADIOMETERN

Zusammenfassung

Dieser für Hersteller und Anwender nützliche technische Bericht wurde vom Technischen Komitee TC 2-47 der CIE ausgearbeitet und beschreibt auf einer gemeinsamen Grundlage die Kennzahlen für UV-Radiometer. Zur Harmonisierung der CIE Dokumente beziehen sich die in diesem Dokument beschriebenen Kennzahlen auf den gemeinsamen internationalen ISO/CIE Standard ISO/CIE 19476:2014(E) (ehemals CIE S 023/E:2013), und auf den, wo immer anwendbar, referenziert wird.

Im Gegensatz zu Photometern, die in ISO/CIE 19476:2014(E) beschrieben werden, können UV-Radiometer für verschiedene aktinische Spektren und unterschiedliche spektrale Bereiche konstruiert sein. Daher werden in diesem Bericht anstelle der einen definierten Referenzspektrum-Quelle (CIE Normlicht A), wie sie in ISO/CIE 19476:2014(E) verwendet wird, drei Referenzspektrum-Quellen vorgeschlagen, um die allgemeine spektrale Charakterisierung von UV-Radiometern für verschiedene Anwendungen zu unterstützen. Die definierten Referenzspektren für die Charakterisierung von UV-Radiometern sind im Anhang aufgeführt.

Dieser Bericht beschreibt außerdem empfänger- und strahlerbasierte Verfahren einschließlich der Messbedingungen und einschränkenden Randbedingungen für die Kalibrierung von UV-Radiometern, die im Labor und in industriellen Anwendungen eingesetzt werden.

1 Introduction

1.1 Objectives

Broadband ultraviolet (UV) radiometers (also called integral measuring UV radiometers) are widely used for measuring UV irradiance or radiant exposure in various industrial, medical, environmental, health and other applications. The accuracy or uncertainty of measurement achievable using these types of radiometers is influenced by many factors, such as the characteristics of the radiometer, operating conditions, environmental conditions and the characteristics of the UV sources that are used to calibrate the radiometer and those that are measured. In particular, the lack of spectral resolving power means that significant measurement errors may occur unnoticed if the radiometer used has a poor match to the intended spectral sensitivity function and/or is not correctly calibrated or used. This has frequently appeared to be the case in the past and problems so caused have raised serious concern. The purpose of this document is to

- give clear definitions for the individual characteristics which can be used for evaluating the performance of broadband UV radiometers;
- recommend methods for the characterization of these radiometers;
- recommend methods for the calibration of these radiometers;
- provide guidelines for the selection and correct use of these radiometers.

This document may be used as a guide for

- manufacturers, in developing good quality UV radiometers;
- calibration laboratories, in performing calibration of these radiometers in a standardized and comparable way;
- users, in the appropriate use of these radiometers to get correct and consistent measurement results for their applications.

For manufacturers and advanced laboratories which are performing a rigorous calibration on a UV radiometer, this document specifies in 6.4 how to perform a full calibration. For public testing laboratories Clause 6.5 specifies how to perform a limited calibration on a UV radiometer for industrial purposes.

1.2 Scope

The UV radiometers considered in this document are restricted to those designed for the wavelength range from 200 nm to 400 nm, i.e. in the spectral bands of UV-A (315 nm to 400 nm), UV-B (280 nm to 315 nm) and part of UV-C (200 nm to 280 nm). The radiation to be measured is also restricted to that from artificial UV sources only. Radiometers used for solar UV measurement are excluded since many additional requirements are important due to the special features of the source (the sun) and changing environmental, weather and geometrical conditions often encountered during measurements. There are already other parties such as the World Meteorological Organization dealing with this issue.

NOTE 1 Although some UV radiometers work outside of the specific ranges defined above, they can be treated in the same way as discussed in this document.

NOTE 2 Spectrally resolving instruments like spectroradiometers are not discussed in this document but will be dealt with in a future CIE Technical Report, currently prepared by CIE TC 2-51.

2 Definitions (General)

For the purposes of this document the following terms and definitions, partly adopted from the ILV (CIE, 2011a), apply.

2.1 radiometer

instrument for measuring radiometric quantities

[SOURCE: CIE S 017/E:2011, term 17-1031]

Note 1 to entry: The radiometric quantities measured may be irradiance, radiance, radiant exposure or radiant power (radiant flux) and these are evaluated over a certain spectral range defined by the responsivity of the radiometer. It usually consists of a radiometer head, an electronic signal converter and an output (display) device. This document is applicable to radiometers for the measurement of UV irradiance and UV radiant exposure.

2.2

UV radiometer

instrument for measuring the total (spectrally-weighted and integrated) radiation, either irradiance or dose (radiant exposure, time-integrated) over a limited spectral band in the ultraviolet region from an artificial source of optical radiation

Note 1 to entry: A UV radiometer may be used to measure radiation from a broadband UV source, such as a high-pressure mercury (Hg) arc lamp or a xenon (Xe) arc lamp, or from a line source such as a low-pressure Hg arc lamp, whose spectrum is concentrated essentially in a single wavelength at about 365 nm, or from UV light emitting diodes (UV-LEDs).

2.3

reference UV radiometer

UV radiometer which is mainly used as a reference standard for calibration of the responsivity of a device under test (DUT) UV radiometer according to a defined action spectrum

Note 1 to entry: The spectral responsivity of a reference UV radiometer should be matched as closely as possible to the action spectrum of interest.

2.4

radiometer head

part of a radiometer containing detector(s) and other components such as filter, diffuser, aperture and attenuator for spectral and spatial corrections of the UV detector

Note 1 to entry: The radiometer head may also include an electronic signal converter and amplifier.

2.5

detector (of optical radiation)

device in which incident optical radiation produces a measurable physical effect

[SOURCE: CIE S 017/E:2011, term 17-296]

2.6

spectral distribution

$$X_{\lambda}(\lambda)$$

quotient of the radiant quantity $dX(\lambda)$ contained in an elementary range, $d\lambda$, of wavelength at the wavelength, λ , by that range

$$X_{\lambda}(\lambda) = \frac{dX(\lambda)}{d\lambda} \quad (0)$$

[SOURCE: CIE S 017/E:2011, term 17-1213, modified: "or luminous or photon " omitted]

Example: The spectral distribution of irradiance is called "spectral irradiance distribution" and is expressed in $\text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$.

Note 1 to entry: Although often interpreted as a ratio of quantities, the physical meaning of $X_{\lambda}(\lambda)$ is that of a distribution of the spectral densities of a quantity, i.e. a derivative of the quantity with respect to wavelength. The spectral distribution $X_{\lambda}(\lambda)$ of a radiant quantity X represents the absolute spectral values of the radiation emitted by a source.

Note 2 to entry: Different to the notation in the ILV (CIE, 2011a, term 17-1084), the relative spectral distribution $S(\lambda)$, which is the ratio of the spectral distribution $X_{\lambda}(\lambda)$ of a radiant quantity $X(\lambda)$ of a source to a fixed reference value $R=X_0$, is named $X_{\lambda, \text{rel}}(\lambda)$ to distinguish more clearly between relative and absolute spectral quantities throughout this document.

2.7

action spectrum

$$A_{\text{act}}(\lambda)$$

function representing the relative spectral effectiveness of optical radiation, for a specified actinic effect, in a specified system; also referred to as: actinic spectrum efficiency of equal intensities of monochromatic radiation for producing that phenomenon in that system as a function of wavelength

[SOURCE: CIE S 017/E:2011, term 17-17]

Note 1 to entry: The action spectrum is essentially a spectral weighting function with a peak value of unity. The subscript "act" specifies the actinic effect.

Note 2 to entry: The action spectrum is dimensionless (of unit 1). If not stated otherwise, it is normalized to its maximum.

Note 3 to entry: An action spectrum usually describes an actinic effect of radiation on radiant sensitive surfaces or bodies like skin, human eye, retina, 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) (DIN 2011), with $A_{\text{act}}(\lambda) = 1$ within the respective interval and $A_{\text{act}}(\lambda) = 0$ outside that interval.

2.8

effective radiant quantity

$$X_{\text{act}}$$

radiant quantity weighted by the action spectrum of the phenomenon of concern

Note 1 to entry: The effective radiant quantity X_{act} (which can be the effective irradiance E_{act} or the effective radiant flux Φ_{act}) of a source in terms of an action spectrum A_{act} can be

$$\text{expressed as } X_{\text{act}} = K \cdot \int_0^{\infty} X_{\lambda}(\lambda) \cdot A_{\text{act}}(\lambda) \cdot d\lambda, \quad (1)$$

where $X_{\lambda}(\lambda)$ is the spectral distribution of the radiometric quantity ($E_{\lambda}(\lambda)$ for spectral irradiance and $\Phi_{\lambda}(\lambda)$ for spectral radiant power, respectively) produced by the source. $A_{\text{act}}(\lambda)$ is the action spectrum function of the phenomenon of concern, and K is the actinic efficacy. The dimension and value of K may depend on the actinic function of interest, but in most cases K is set to unity.

2.9

effective radiant exposure

$$H_{\text{act}}$$

time integral of the effective irradiance, E_{act} , over the period of exposure time, t

$$H_{\text{act}} = \int_{t_1}^{t_2} E_{\text{act}}(t) \cdot dt \quad (2)$$

2.10

spectral responsivity

$$s(\lambda)$$

quotient of the detector output, $dY(\lambda)$, by the monochromatic detector input, $dX_e(\lambda) = X_{e,\lambda}(\lambda)d\lambda$, in the wavelength interval, $d\lambda$, as a function of wavelength, λ

$$s(\lambda) = \frac{dY(\lambda)}{dX_e(\lambda)} \quad (3)$$

[SOURCE: CIE S 017/E:2011, term 17-1229]

Note 1 to entry: The spectral responsivity may also depend on the spectral radiant quantity level. The subscript "e" to emphasize radiometric quantities is omitted elsewhere within this document.

Note 2 to entry: The relative spectral responsivity, $s_{\text{rel}}(\lambda)$, is the ratio of the spectral responsivity, $s(\lambda)$, to a given reference value, e.g. its peak value, s_0 , at the wavelength of peak response, λ_0 , and consequentially:

$$s(\lambda) = s_0 \cdot s_{\text{rel}}(\lambda), \quad (4)$$

where $s(\lambda)$ is normalized at λ_0 . The units of s_0 and $s(\lambda)$ depend on the measured input quantity (e.g. irradiance or radiant flux) and the detector output quantity (e.g. current, voltage or count rate). Therefore, the unit of the spectral responsivity may be for example $[\text{A} \cdot \text{W}^{-1} \cdot \text{m}^2]$ in case of spectral irradiance responsivity or $[\text{A} \cdot \text{W}^{-1}]$ in case of spectral radiant flux responsivity.

Note 3 to entry: A UV radiometer is usually designed to measure effective irradiance and/or effective radiant exposure according to a specific action spectrum. This requires the relative spectral responsivity of its radiometer head to match the action spectrum of concern, i.e. $s_{\text{rel}}(\lambda) \mapsto A_{\text{act}}(\lambda)$.

2.11 effective responsivity

$s_{X,\text{act}}$

quotient of the output signal, Y , of a radiometer head by the effective radiant quantity, X_{act} , as input signal

$$s_{X,\text{act}} = \frac{Y}{X_{\text{act}}} \quad (5)$$

Note 1 to entry: The output signal, Y , of a UV radiometer is expressed by:

$$Y = \int_0^{\infty} X_{\lambda}(\lambda) \cdot s(\lambda) d\lambda, \quad (6)$$

where $X_{\lambda}(\lambda)$ is the spectral distribution of the radiant input quantity and $s(\lambda)$ is the spectral responsivity of the detector. The effective radiant quantity, X_{act} , as input signal is expressed according to Equation (1) in 2.8.

The effective responsivity thus can be expressed by

$$s_{X,\text{act}} = \frac{s_0}{K} \cdot \frac{\int_0^{\infty} X_{\lambda}(\lambda) \cdot s_{\text{rel}}(\lambda) d\lambda}{\int_0^{\infty} X_{\lambda}(\lambda) \cdot A_{\text{act}}(\lambda) d\lambda}, \quad (7)$$

where s_0 is the peak value of the spectral responsivity, K is the actinic efficacy, $X_{\lambda}(\lambda)$ is the spectral distribution of the radiant input quantity, $s_{\text{rel}}(\lambda)$ is the relative spectral responsivity of the detector and $A_{\text{act}}(\lambda)$ is the action spectrum of the phenomenon of concern.

Note 2 to entry: Depending on the type of radiometer, the unit of the spectral responsivity $s(\lambda)$ in Equation (6) is given either by the responsivity of the radiometer head or by the total responsivity of the UV radiometer (including amplifier and display components). No distinction with respect to this will be made in the document.

Note 3 to entry: The calibration of a UV irradiance radiometer requires the determination of its effective responsivity, $s_{X,\text{act}}$.

Note 4 to entry: From Equation (6) it follows that, if the relative spectral responsivity of the UV radiometer being used is not exactly equal to the relative distribution of the actinic action spectrum, then the effective responsivity strongly depends on the relative spectral distribution of the source used to produce the radiometric quantity X . This has to be considered especially if the source used during the calibration differs from the reference sources defined for the calibration of the UV radiometer or if the source being measured in the field differs from the source that was used to calibrate the instrument. In this case, the effective responsivity for the designated calibration source must be given together with the spectral mismatch correction factor for the source of interest (see 4.3).

2.12**calibration source**

source used to produce the required radiant quantity X (irradiance, radiance or radiant power) at the radiometer head during a source-based quasi-monochromatic or direct broad-band calibration

Note 1 to entry: A calibration source has to be stable with respect to its electrical operating condition and its optical output. Spectral changes of the calibration source should be negligible (i.e. significantly below the expected uncertainty of the measurements) during the period of time used for and in between calibration. If a calibration source is used for the direct calibration of a UV radiometer against the source, its effective radiant quantity X_{act} (see 2.8) should be known and reproducible.

Note 2 to entry: Where applicable, the calibration source should match as close as possible the source used in the final application of the UV radiometer. If used for the calibration of UV detectors for a defined action spectrum but arbitrary applications, the spectral distribution of the calibration source should cover the whole spectral range of interest. In this case and if possible, the spectral distribution of the calibration source should be close to that of the reference-spectrum source (see 2.13) for the action spectrum of interest to minimize spectral mismatch.

2.13**reference-spectrum source**

specific source, represented by an idealized spectrum of a real source or a theoretical spectral distribution, which is designated for a specific action spectrum and is stated as a nominal source to which the actinic responsivity of a UV radiometer should generally be referred

Note 1 to entry: Depending on the action spectrum, the reference-spectrum source can be either represented by an idealized spectrum of a real source (which is most often used for the actinic function of interest) or as a theoretical spectral distribution, given in tabulated form or as a mathematical function (see Annex A.1). A reference-spectrum source is intended for the general evaluation of the effective responsivity of a particular UV radiometer that is used to perform measurements with the related action spectrum. It is an application-source independent reference. In Annex A.1 the relative spectral distribution of a reference-spectrum source $X_{\lambda, R, \text{rel}}(\lambda)$ is given normalized to one.

Note 2 to entry: Reference-spectrum sources with defined spectral distributions allow the overall effective responsivity of a UV radiometer to be quantified and are useful for comparisons between different UV radiometers.

Note 3 to entry: More than one reference-spectrum source may be used in conjunction with a single actinic spectrum.

Note 4 to entry: The reference-spectrum source, which allows the broad band characterization of a UV radiometer, must be distinguished from a calibration source. For example, a low pressure mercury lamp is often used as a calibration source to calibrate detectors in the field of water disinfection in combination with the microbicidal action spectrum $A_{\text{mic}}(\lambda)$. Although the spectral range of the action spectrum is defined over a broader wavelength range, only the 253,65 nm line of the mercury lamp is used to measure the effective responsivity of the used UV radiometers for this spectrally limited line. This determines a calibration value for the corresponding UV radiometer under a certain working condition, without information about the spectral match of the detector with respect to the actinic function. However, in the special application of water disinfection low pressure mercury lamps are also used as radiation sources, so it is evident to use this type of lamps also as calibration source. But, to determine a unique number for the spectral mismatch with respect to the actinic function of the used UV radiometer according to 4.3, a defined broad-band reference-spectrum source should be used.

3 Quality indices

The following quality indices for UV radiometers are used to characterize their performance. They are properties of the UV radiometer, and are not intended to be used for calculations of measurement uncertainty. The name of each quality index has been taken from the physical effect that influences its value for easy understanding of its meaning. The names, their

symbols and abbreviations defined in this clause are kept consistent with those used for the characterization of photometers in the Joint ISO/CIE International Standard ISO/CIE 19476:2014(E) (ISO/CIE, 2014) whenever possible.

3.1

initial adjustment index

$$f_{\text{adj}}$$

index describing the absolute relative deviation of the UV radiometer indication from the corresponding reference value

[SOURCE: ISO/CIE 19476:2014, 3.2.1, modified: “photometer” replaced by “UV radiometer”]

3.2

spectral mismatch index

$$f'_{1,\text{act}}$$

index describing the deviation of the relative spectral responsivity of the radiometer head from the designated action spectrum using the designated reference source

3.3

short-wavelength range response index

$$f_{\text{sh,act}}$$

index describing the responsivity of the radiometer head at wavelengths shorter than the spectral range of the designated action spectrum

3.4

long-wavelength range response index

$$f_{\text{lo,act}}$$

index describing the responsivity of the radiometer head at wavelengths longer than the spectral range of the designated action spectrum

3.5

directional response index

$$f_2$$

index describing the deviation from the ideal cosine law of the responsivity of the radiometer head to radiation incident at angles other than normal to the reference plane of the head

3.6

linearity index

$$f_3$$

index describing the deviation of the responsivity of the radiometer for different levels of irradiance from linearity

3.7

display-unit index

$$f_4$$

index describing the influence of the display unit of the radiometer on the measurement results

3.8

fatigue index

$$f_5$$

index describing the reversible change of the responsivity of the radiometer over time under constant irradiation

3.9 temperature dependence index

 $f_{6,T}$

index describing the influence of ambient temperature on the radiometer responsivity when the ambient temperature differs from that at the time of calibration

3.10 humidity test index

 $f_{6,H}$

index describing the stability of the radiometer with respect to humidity

3.11 modulated radiation index

 f_7

index describing the influence of modulated radiation at various frequencies, as opposed to that of DC-operated lamps

3.12 polarization response index

 f_8

index describing the influence of polarized radiation on the responsivity of the radiometer

[SOURCE: ISO/CIE 19476:2014, 3.2.19, modified: “light” replaced by “radiation”, “photometer” replaced by “radiometer”.]

3.13 spatial response index

 f_9

index describing the influence of non-uniform irradiation incident on the radiometer within the acceptance aperture

3.14 range change index

 f_{11}

index describing the influence of range settings of display units or amplifiers

[SOURCE: ISO/CIE 19476:2014, 3.2.21]

4 Properties of UV radiometers

4.1 Initial adjustment

The initial adjustment index is the absolute value of the relative deviation of the UV radiometer indication from the corresponding reference value. If the measured quantity is irradiance, the quality index for initial adjustment, the initial adjustment index, $f_{\text{adj}} = |E'_{\text{cal}}/E_{\text{cal}} - 1|$, is the absolute value of the relative deviation of the radiometer indication, E'_{cal} , from the corresponding reference value, E_{cal} .

The manufacturer will usually adjust the radiometer indication to the reference value, and in this case $f_{\text{adj}} = 0$, but the associated uncertainty of f_{adj} will correspond to the uncertainty of the initial calibration process. This uncertainty should be stated together with the value of the initial adjustment index, f_{adj} .

NOTE 1 For low-cost radiometers, the procedures for the adjustment of their indications are often simplified, and also the uncertainties associated with the values of the used reference standards are larger, which significantly increases the value of this quality index and its associated uncertainty.

NOTE 2 For the determination of f_{adj} boundary conditions as given in Clause 5 need to be fulfilled.

4.2 Effective responsivity against a reference-spectrum source

In Equation (6) it was defined that the effective responsivity, $s_{X,act}$, of a UV radiometer is determined by its spectral responsivity, $s(\lambda)$, the action spectrum, $A_{act}(\lambda)$, of the considered effect and the absolute spectral distribution, $X_{\lambda}(\lambda)$, of the radiant quantity of the source. For a particular source, e.g. a defined reference source R, this equation can be rewritten as

$$s_{X,act,R} = \frac{s_0}{K} \cdot \frac{\int_0^{\infty} X_{\lambda,R,rel}(\lambda) \cdot s_{rel}(\lambda) d\lambda}{\int_0^{\infty} X_{\lambda,R,rel}(\lambda) \cdot A_{act}(\lambda) d\lambda} \quad (8)$$

where

$X_{\lambda,R,rel}(\lambda)$ is the relative spectral distribution of the radiant quantity X of the reference-spectrum source R;

s_0 , $s_{rel}(\lambda)$ are the peak value and the relative spectral responsivity of the radiometer head, respectively;

$A_{act}(\lambda)$ is the action spectrum of the actinic effect of interest;

K is the actinic efficacy.

Equation (8) shows that only the relative spectral distribution, $X_{\lambda,R,rel}(\lambda)$, of the reference-spectrum source is required for the determination of the effective responsivity, $s_{X,act,R}$, for a detector with a given relative spectral responsivity, $s_{rel}(\lambda)$, and a given action spectrum. So, the concept of using a reference-spectrum source for the determination of the integral actinic responsivity of a UV radiometer is very similar to the use of Illuminant A in photometry to determine the photometric responsivity of a photometric detector.

The effective responsivity may be determined by calculation, in which case the absolute spectral responsivity of the UV radiometer must be calibrated, or it may be determined by measurement of a defined calibration source, in which case the absolute effective irradiance, effective radiant power or effective radiant exposure (using the relevant action spectrum) of the source must be calibrated.

Ideally, the relative spectral responsivity of a UV radiometer should match that of the desired action spectrum. However, Equation (8) implies that even a radiometer with a relative response which is a poor match to the action spectrum could still be calibrated to measure a radiant source, if that particular source has the same relative spectral distribution as the source which was used during calibration. However, such a radiometer could be completely unsuitable to monitor e.g. the ageing of even this particular source, because the relative spectral distribution of the source might change in a wavelength-dependent fashion during its lifetime.

To account for the spectral mismatch of sources and detectors, a spectral mismatch correction, which may change during the lifetime of the detector and during the lifetime of the source which is measured, has to be applied (see Equation (10)).

NOTE For a given action spectrum, the effective responsivity of a UV radiometer is in general not a constant, since its value depends on the spectral distribution of the source; the effective responsivity is only independent of the source if the normalized relative spectral responsivity defined by Equation (6) is identical to the action spectrum considered, which is generally very difficult to achieve. Therefore, the calibration and determination of the effective responsivity, $s_{act,R}$, is only valid for measurements on sources that have the same

spectral distribution as the reference-spectrum source unless a spectral mismatch correction is applied.

4.3 Spectral matching

- Spectral mismatch correction factor

According to Equation (8) a systematic deviation from the estimated value will result when a UV radiometer, which is characterized against a reference-spectrum source R with the relative spectral distribution, $X_{\lambda,R,rel}(\lambda)$, is used to measure radiation produced by a different (calibration) source Z of different spectral distribution, $X_{\lambda,Z,rel}(\lambda)$.

Such a deviation can be considered by a **spectral mismatch**, $a_{act,R,Z}^*$, defined as the ratio of the effective responsivity of the radiometer head with respect to the radiant quantity of the test source, $s_{X,act,Z}$, to the effective responsivity with respect to the reference source, $s_{X,act,R}$.

$$a_{act,R,Z}^* = \frac{s_{X,act,Z}}{s_{X,act,R}} = \frac{\int_0^\infty X_{\lambda,Z,rel}(\lambda) \cdot s_{rel}(\lambda) \cdot d\lambda}{\int_0^\infty X_{\lambda,Z,rel}(\lambda) \cdot A_{act}(\lambda) \cdot d\lambda} \bigg/ \frac{\int_0^\infty X_{\lambda,R,rel}(\lambda) \cdot s_{rel}(\lambda) \cdot d\lambda}{\int_0^\infty X_{\lambda,R,rel}(\lambda) \cdot A_{act}(\lambda) \cdot d\lambda} \quad (9)$$

where $X_{\lambda,R,rel}(\lambda)$, $X_{\lambda,Z,rel}(\lambda)$ are the relative spectral distributions of the reference-spectrum source R and that of source Z, respectively.

The reciprocal of this spectral mismatch, $F_{act,R,Z}^* = 1/a_{act,R,Z}^*$, is called the **spectral mismatch correction factor** and can be used to correct measurement results:

$$Y_R = Y_Z \cdot F_{act,R,Z}^* \quad (10)$$

where

Y_R is the corrected value with respect to the reference-spectrum source R;

Y_Z is the (un-corrected) reading of the radiometer when measuring the source Z.

The spectral mismatch can be converted into the specific mismatch index, $f_{1,act}(Z)$, given by:

$$f_{1,act}(Z) = a_{act,R,Z}^* - 1. \quad (11)$$

NOTE 1 $f_{1,act}(Z)$ is an index which indicates the magnitude of deviation of the results measured by the radiometer on different sources. For perfect spectral matching (the relative spectral responsivity, $s_{rel}(\lambda)$, of a radiometer is identical to the prescribed action spectrum, $A_{act}(\lambda)$), $f_{1,act}(Z) = 0$, regardless of the type of source it is calibrated against or it measures.

NOTE 2 $f_{1,act}(Z)$ is not a unique figure for a radiometer but associated with the source and action spectrum specified.

The spectral distributions of some commonly used UV sources are listed in Annex A.1

- General mismatch index

For optimizing the spectral matching of a radiometer head to a desired action spectrum, $A_{act}(\lambda)$, the spectral mismatch index, $f'_{1,act}$, calculated by the following formula should be used: