THEMATIC NETWORK FOR ULTRAVIOLET MEASUREMENTS

Working Group 1: Guidance for UV power meter classification for particular applications

Characterizing the Performance of Integral Measuring UV-Meters

Final Report
November 2000

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FOREWORD

ACKNOWLEDGEMENTS

FOREWORD

Working Group 1 was established by the EU Thematic Network for Ultraviolet Measurements in March 1998 to work with problems related with industrial UV-measurements. European industry has problems with manufacturing UV radiometers, because there are no internationally accepted methods for characterising and classifying the manufactured devices. The same problem exists with customers, as they have no means of determining the quality of the UV-meters that they use.

As compared to photometry, where the situation of standardisation is much better, characterisation of UV radiometers is more complicated. In photometry, there is only one action spectrum, the photopic response of eye, to consider. In UV region, many different action spectra exist, and the characterisation methods have to be applicable for any action spectrum.

The document consists of two parts. The first part "Characterizing the performance of integral measuring UV-meters" defines figures of merit for UV power meters and methods to evaluate these figures. There exists a document CIE Publication 69, *Methods of characterizing illuminance meters and luminance meters* (1987) which defines similar characterisation techniques for photometers. The terminology used in this document has been chosen to be similar to the CIE document wherever applicable for consistency. Chapters 5 and 6 of this document give instructions on labelling devices and a recommendation for instrument classification. It is proposed that at this stage three classes *A*, *B*, and *C* will be used. In future when technology develops, a high-accuracy class *L* (consistent with CIE 69) could be taken into use.

The appendix part of this document gives practical advice on how to perform specific instrument calibrations. The instructions are intended to reduce uncertainties arising in the characterisation. Chapter 4 defines standard lamps, the defined spectra of which may be used in spectral calculations. This database has been chosen in such a way that most light sources used in UV-measurements are covered. The tabulated spectra represent typical specimens of each lamp type.

This document has a status of recommendation. Manufacturers and end users are encouraged to test the proposed methods and give feedback if necessary. The document will be maintained at the web-pages of the Thematic Network (http://metrology.hut.fi/uvnet/). This document with the given comments will be used as background information when future work with standardisation is carried out e.g. within CIE.

I cannot finish this work without feeling deep gratitude. Many thanks to the members of Working Group 1, assistance of working Group 3, and support members who have engaged themselves to complete this recommendation to such large extent.

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1 Scope and fields of application

An integrally measuring UV-meter is an instrument the relative spectral responsivity of which is matched to the action spectrum of the photochemical, photobiological or photovoltaic effect under consideration. According to the van Krefeld law, the actinic effects of radiation are defined by actinic radiant quantities as

$$X_{act} = \int_0^\infty s(\lambda)_{act,rel} \cdot X_{e\lambda} \cdot d\lambda \,. \qquad (0)$$

The index "act" describes the effect under consideration. $s(\lambda)_{\mathrm{act,rel}}$ is the relative spectral weighting function of the considered effect (action spectrum), $X_{e\lambda}(\lambda)$ the spectral radiant quantity incident on the receiver. Matching of the relative spectral responsivity $s(\lambda)_{\mathrm{rel}}$ of the integrally measuring radiometer to $s(\lambda)_{\mathrm{act,rel}}$ is usually performed by appropriate optical filtering of the incident radiation. Actinic effects, such as photolysis, UV curing, erythema etc., depend on the irradiance level, spectral power distribution of radiation, action spectrum and exposure time. This is why an actinic radiometer should be characterised first of all by the kind of actinic effect of radiation to be measured and the measuring range and then by figures which specify the uncertainties of actinic measurement. Respective uncertainties are produced by imperfect calibration, response of the instrument to radiation which is outside of the action spectrum, deviations from cosine response, non-linearity, fatigue, dependencies of response on ambient temperature, modulation and polarisation of radiation, by non-uniform irradiation of the radiometer, offset and noise of the instrument and change of the measuring range.

This report is not an officially agreed document of standardisation, but is recommended for study and application by manufacturers as well as by users of actinic radiometers. Here, only radiometers that integrally measure in the UV range are characterised with respect to performance.

The weighting function $s(\lambda)_{\mathrm{act,rel}}$ need not describe a real actinic effect in each case, but can be an artificial one, as for instance a rectangular function over a distinct UV range (UV-A, UV-B and UV-C).

2 Definitions

The following definitions, symbols and abbreviations apply.

2.1 Characteristics

The following characteristics of integral measuring radiometers influence the uncertainty of measurements, and are used for a characterisation of the performance. The name of each characteristic has been taken from the physical effect influencing its quantity for easy memorising of its meaning.

2.1.1 Calibration uncertainty u_{cal}

The calibration uncertainty u_{cal} describes the uncertainty provided by the calibration of the radiometer. It must include the transfer uncertainty of the transfer standard.

2.1.2 Short wavelength range response characteristic u

The short wavelength range response characteristic u describes the responsivity of the radiometer head at wavelengths shorter than the designated weighting function.

2.1.3 Long wavelength range response characteristic r

The long wavelength range response characteristic r describes the responsivity of the radiometer head at wavelengths longer than the designated weighting function.

2.1.4 Directional response characteristic f_2

The directional response characteristic f_2 describes the responsivity of the radiometer head to radiation incident at angles other than perpendicular (cosine law).

2.1.5 Linearity characteristic f_3

The linearity characteristic f_3 describes the variation of the radiometer responsivity for different levels of radiation.

2.1.6 Display unit characteristic f_4

The display unit characteristic f_4 describes the influence of the analogue or digital display unit of the radiometer.

2.1.7 Fatigue characteristic f_5

The fatigue characteristic f_5 describes the reversible change over time of the radiometer responsivity under constant irradiation.

2.1.8 Temperature dependence characteristic f_6

The temperature dependence characteristic f_6 describes the influence of ambient temperature different from calibration temperature.

2.1.9 Modulated radiation characteristic f_7

The modulated radiation characteristic f_7 describes the influence of modulated radiation at various frequencies, as opposed to that of DC-operated lamps.

2.1.10 Polarisation response characteristic f_8

The polarisation response characteristic f_8 describes the influence of polarised radiation on the responsivity of the radiometer.

2.1.11 Spatial response characteristic f_9

The spatial response characteristic f_9 describes the influence of non-uniform irradiation of radiometers.

2.1.12 Range change characteristic f_{11}

The range change characteristic f_{11} describes the influence of range settings of display units or amplifiers.

2.1.13 Ageing

Ageing is the irreversible temporal change of the responsivity of a radiometer.

> *NOTE: The influence due to ageing can be reduced by re-calibrating in shorter time intervals. A change in relative spectral responsivity can not be corrected by re-calibration.*

3 Calibration

3.1 Requirements

The radiometer must be calibrated for spectral responsivity at specific wavelengths across the wavelength range of the designated weighting function, and the calibration uncertainty evaluated at each of these wavelengths. These uncertainty values will be included in the manufacturer's specification.

3.2 Uncertainties

The calibration of a radiometer has an uncertainty, which results from the uncertainty of measurement and from the uncertainty of the calibration standard. The value of the latter has to be taken from the calibration certificate of the standard and has to be stated with the characteristics of the radiometer. Other uncertainties can result from:

- ageing of the standard
- uncertainty of the working standard, if used
- uncertainty of the measurement of the electrical quantities of the standard and its geometrical adjustment
- uncertainty due to the calibration conditions
- stray radiation
- temperature changing of the radiometer by heating caused by the radiation of the standard
- influence of fluorescence
- other influence on the radiometer for ambient conditions, which have not been mentioned so far, but existed during calibration

4 Property of radiometers

4.1 Spectral responsivity

The relative spectral responsivity $s(\lambda)_{rel}$ of an integral measuring radiometer shall match to a prescribed weighting function $s(\lambda)_{act,rel}$.

The relative spectral responsivity of a radiometer head shall be specified within the complete wavelength range for the prescribed weighting function and tabulated in steps of preferably 1 nm or less. If spectral parameters exist only with larger steps, they need to be interpolated. Additionally, the relative spectral responsivity may be shown together with the target function by means of a diagram. For comparison of actual and target function, $s(\lambda)_{act,rel}$ should be presented by means of $s^*(\lambda)_{act,rel}$ according to Eq. (1). This performs a practical normalisation of the relative spectral responsivity taking into account the calibration source.

$$s^*(\lambda)_{rel} = \frac{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{c}} \cdot s(\lambda)_{act,rel} \cdot \mathrm{d}\lambda}{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{c}} \cdot s(\lambda)_{rel} \cdot \mathrm{d}\lambda} \cdot s(\lambda)_{rel}, \qquad (1)$$

where

$S_{\lambda,c}$	spectral distribution of the illuminant used for calibration
$s(\lambda)_{act,rel}$	relative spectral actinic weighting function
$s(\lambda)_{rel}$	relative spectral responsivity of the radiometer head
$s^*(\lambda)_{rel}$	normalised relative spectral responsivity for the calibration source.

4.2 Characterisation known of spectral matching

Different techniques are available for characterising the quality of the spectral match of a real radiometer head towards the assigned actinic weighting function.

4.2.1 Spectral correction factor

For a spectral evaluation using the relative spectral responsivity data of a radiometer which differ in certain spectral ranges from the prescribed weighting function, wrong measurement results are obtained. When the responsivity is spectrally integrated, such differences may compensate each other. Comparing two relative spectral distributions, e.g. source Z and the calibration source c, possible deviations may compensate each other this way.

The ratio of the radiometric responsivity of the radiometer head irradiated by the source Z to the radiometric responsivity of the same radiometer head irradiated by the calibration source c leads to the relative responsivity $a(Z)$ according to Eq. (2),

$$a(Z) = \frac{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{c}} \cdot s(\lambda)_{act,rel} \cdot \mathrm{d}\lambda}{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{c}} \cdot s(\lambda)_{rel} \cdot \mathrm{d}\lambda} \cdot \frac{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{Z}} \cdot s(\lambda)_{rel} \cdot \mathrm{d}\lambda}{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{Z}} \cdot s(\lambda)_{act,rel} \cdot \mathrm{d}\lambda}, \tag{2}$$

where

$S_{\lambda,c}$	spectral distribution of the source used for calibration
$S_{\lambda,Z}$	spectral distribution of the source in a particular application
$s(\lambda)_{act,rel}$	relative spectral actinic weighting function
$s(\lambda)_{rel}$	relative spectral responsivity of the radiometer head.

If measurement of a source Z is carried out with the radiometer, previously calibrated with the calibration source c , the reading can be corrected according to the Eq. (3),

$$Y = \frac{Y_Z}{a(Z\ )}, \tag{3}$$

where

Y	correct value
Y_Z	reading of the radiometer when measuring the source Z
$a(Z)$	relative responsivity according to Eq. (2), its reciprocal is also known as spectral correction factor.

The remaining deviation $f_1(Z)$ is given according to Eq. (4),

$$f_1(Z) = a(Z) - 1 = \frac{s_Z}{s_c} - 1, \tag{4}$$

where

s_Z	radiometric responsivity of the radiometer head using source Z
s_C	radiometric responsivity of the radiometer head using the calibration source c
$a(Z)$	relative responsivity according to Eq. (2).

A representative set of generally used sources in UV-applications are listed in the Appendix. It is recommended for manufacturers to state relevant figures for $f_1(Z)$ using the mentioned sources.

4.2.2 Integral characterisation f'_1

For optimising the spectral matching of a radiometer head to a desired relative spectral actinic weighting function during the manufacturing process the following characterisation, defined by Eq. (5), should be used,

$$f_1' = \frac{\int_0^\infty \left| s(\lambda)^*{}_{\mathrm{rel}} - s(\lambda)_{act,rel} \right| \cdot \mathrm{d}\lambda}{\int_0^\infty s(\lambda)_{act,rel} \cdot \mathrm{d}\lambda}, \qquad (5)$$

where

$s(\lambda)_{act,rel}$	relative spectral actinic weighting function
$s\,{}^*(\lambda)_{,rel}$	normalised relative spectral responsivity according to Eq. (1).

The advantage of this definition is that there is no irradiating source included; it compares only the actual responsivity with the target function. The definition generally leads to larger figures compared to the definition of $f_1(Z)$. It must be noted, that f'_1 can not be used for correcting measurements.

4.2.3 Integral characterisation f_{index}

The definition for f'_1 according to Eq. (5) can be modified so that a spectral distribution of a source is included. This leads to the definition according to Eq. (6),

$$f_{\mathrm{index}} = \frac{\int_0^\infty \left| s^*(\lambda)_{\mathrm{rel}} - s(\lambda)_{act,rel} \right| \cdot S_{\lambda,Z} \cdot \mathrm{d}\lambda}{\int_0^\infty s(\lambda)_{act,rel} \cdot S_{\lambda,Z} \cdot \mathrm{d}\lambda}, \qquad (6)$$

where

$S_{\lambda,Z}$	spectral distribution of the source in a particular application
$s(\lambda)_{act,rel}$	relative spectral actinic weighting function
$s(\lambda)_{rel}$	relative spectral responsivity of the radiometer head
$s\,{}^*(\lambda)_{rel}$	normalised relative spectral responsivity considering the calibration source.

A representative set of generally used sources in UV-applications is listed in the Appendix. Manufacturers may state relevant figures for f_{index} using the mentioned sources.

This definition is not suitable to be used for optimising the spectral matching to a target function, since it is always possible to minimise f_{index} by selection of an appropriate lamp spectral distribution. It must be noted that f_{index} can not be used for correcting measurements.

4.3 Short wavelength range response

The short wavelength range response u of a radiometer head is the ratio of the signal Y_{s} when the head is irradiated by a defined UV source combined with a specified short pass UV filter to the signal Y when it is irradiated by the same source without the filter, according to Eq. (7),

$$u = \left| \frac{Y_s}{Y} - u_0 \right|, \tag{7}$$

where u_0 is given by Eq. (8),

$$u_0 = \frac{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{s}} \cdot \tau(\lambda) \cdot s(\lambda)_{act,rel} \cdot \mathrm{d}\lambda}{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{s}} \cdot s(\lambda)_{act,rel} \cdot \mathrm{d}\lambda}, \tag{8}$$

where

$\tau(\lambda)$	spectral transmittance of the filter for determining the short wavelength range response
$S_{\lambda,s}$	spectral distribution of the lamp used for determining the short wavelength range response
$s(\lambda)_{\mathrm{act,rel}}$	relative spectral weighting function.

The short wavelength range response is to be determined by irradiating the radiometer by a UV source and appropriate filter, suitable for the weighting function under consideration. The Appendix lists sources and filters applicable for radiometer heads matched for a variety of actinic weighting functions.

4.4 Long wavelength range response

The long wavelength range response of a radiometer head is according to Eq. (9) the ratio of the signal Y_l, when the head is irradiated by a defined source, combined with a specified long pass optical filter, to the signal Y when it is irradiated by the same source without the filter.

$$r = \left| \frac{Y_l}{Y} - r_0 \right|, \tag{9}$$

where r_0 is according to Eq. (10),

$$r_0 = \frac{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{A}} \cdot \tau(\lambda) \cdot s(\lambda)_{eff,rel} \cdot \mathrm{d}\lambda}{\int_0^\infty \mathrm{S}_{\lambda,\mathrm{A}} \cdot s(\lambda)_{eff,rel} \cdot \mathrm{d}\lambda}, \tag{10}$$

where

$\tau(\lambda)$	spectral transmittance of the filter for determining the long wavelength range response
$\mathrm{S}_{\lambda,\mathrm{A}}$	spectral distribution of the lamp used for determining the long wavelength range response.

The long wavelength range response should be measured by irradiating the radiometer head with a source, emitting a sufficient radiation level in the long wave length range of the considered weighting function. The combined filter must have suitable blocking characteristics for the long wavelength range of the considered weighting function. The Appendix lists sources and filters applicable for radiometer heads matched for a variety of actinic weighting functions.

4.5 Directional response

4.5.1 General

The effect of incident radiation on the acceptance area of the radiometer head depends on the angle of incidence. The directional response function (evaluation of the incident radiation as a function of the angle of incidence) is determined by the shape and the optical properties of the acceptance area as well as the geometric and optical construction of the radiometer head.

4.5.2 Measurement

For the measurement of directional response, a point radiation source shall be placed in front of the radiometer head. The distance in-between must be greater than the radiometric limiting distance. Special precautions should be taken to exclude stray radiation from the acceptance area of the radiometer head. The radiometer head has to be adjusted with its optical axis towards the source.

Rotation of the radiometer head around a horizontal or vertical axis varies the angle of incidence referred to the centre of the acceptance area of the radiometer head. The centre of revolution should be coincident with the centre of the acceptance area. Measurements of the signal as a function of the angle of incidence shall be carried out in at least two mutually perpendicular planes.

> *NOTE 1: On adapters using radiation scattering materials, the reference point for the rotation has to be stated.*
>
> *NOTE 2: For radiometer heads with a non-linear relationship between input quantity and output signal, the measurement should be conducted at a constant signal level. Then the irradiance must be changed in a defined way (e.g. change of distance). Otherwise the result must be corrected via the measured input-output characteristic of the radiometer head.*

4.5.3 Evaluation

For a radiometer the systematic deviation in directional response to the incident radiation is given according to Eq. (11),

$$f_2^*(\varepsilon,\varphi)=\left|\frac{Y(\varepsilon,\varphi)}{Y(\varepsilon=0^\circ,\varphi)\cdot\cos\varepsilon}-1\right|, \tag{11}$$

where

$Y(\varepsilon,\varphi)$ output signal as a function of the angle of incidence

ε,φ according to Fig. 1.

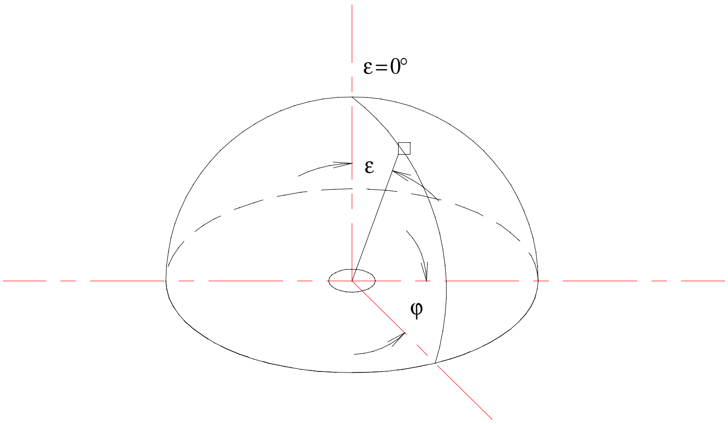

Figure 1. Co-ordinates for evaluation of directional response.

For characterising the directional response, the characteristic f_2 according to Eq. (12) is used,

$$f_2 = \int_0^{\frac{85^\circ \cdot \pi}{180^\circ}} \left| f_2^*(\varepsilon, \varphi = 0) \right| \cdot \sin 2\varepsilon \mathrm{d}\varepsilon \,. \tag{12}$$

NOTE 1: The angle range beyond the limits of integration of Eq. (12), is excluded, since it leads to results not relevant for practical use.

NOTE 2: According to that definition the characteristic f_2 is defined as mean value of cosine errors averaged over nearly the total half sphere of reception. The above parameter may be misleading in the case of measurement of solar global radiation, because of the large proportion due to direct solar irradiance on the horizontal plane, with the exception of overcast sky condition. The real effective cosine error corresponds to the angular position of the sun. This effect becomes greater, the lower the cloud cover and the solar zenith angle are. In the case of UV-global solar radiation this contribution to the error decreases with decrease of the wavelength. However even in the case of UV-A radiation the portion of "direct cosine error" has to be considered if the sun is high. Equivalent remarks must be taken into account on measurements in solariums with different fluorescent lamps at different places.

4.6 Linearity

4.6.1 General

The input - output characteristic of a radiometer describes the relation between the output quantity (reading) and the input quantity.

The linearity of a radiometer is the property whereby the output quantity of the detector is proportional to the input quantity.

In general, perfect linearity of a radiometer can not be assured.

4.6.2 Measurement

For the measurement of the input - output characteristic and determination of the deviation from linearity, the radiometer head has to be irradiated continuously or in steps with defined levels of irradiance. With each level of input quantity, the output quantity (reading) shall be recorded.

For performing such measurements, certain setups for varying the irradiance on the radiometer head in a stepwise manner (in general with a step ratio of 1:2) are mentioned in the literature.

The measurements for high levels of irradiance may also be determined by testing the linearity of the radiometer's components (radiometer head, amplifier) separately.

4.6.3 Characterisation

The function of systematic deviation $f^*_3(Y)$ in linear response of radiometers is given in Eq. (13),

$$f_3^*(Y) = \frac{Y}{Y_{\max}} \cdot \frac{X_{\max}}{X} - 1\,, \qquad (13)$$

where

Y	output signal due to irradiance on the radiometer head with an input quantity X
$X_{\max}$	input value corresponding to the maximum output signal $Y_{\max}$ (largest value of the measurement range)
$Y_{\max}$	output signal due to irradiation on the radiometer head with the input $X_{\max}$.

The number of measurement points for determining $f^*_3(Y)$ it must be chosen sufficiently large in order to ensure that the transfer function is completely covered.

To characterise the deviation in linearity within the different ranges, the characteristic f_3 according to Eq. (14) is used. It equals the maximum value over all measurement ranges of the function of systematic deviation $f^*_3(Y)$ in Eq. (13).

$$f_3 = f_3^*(Y)_{\max}\,. \qquad (14)$$

4.7 Display unit

4.7.1 General

The measurement accuracy of the radiometer's analogue display is determined by the class of the analogue apparatus.

NOTE: The classification gives the maximum output uncertainty referred to the full-scale reading.

4.7.2 Characterisation

The deviation of a radiometer due to the class of analogue display is characterised by the parameter f_4 according to Eq. (15),

$$f_4 = k \cdot [\text{class}], \tag{15}$$

where

k	factor due to changing output range (e.g. k = 10 when the switching of the measurement range is at the ratio of 1:10).

and is defined according to Eq. (16),

$$k = y_{B,\max} / y_{A,\max}, \tag{16}$$

where

$Y_{A,max}$	full scale reading in the more sensitive range *A*
$Y_{B,max}$	full scale reading in the less sensitive range *B*.

NOTE: The characterisation by the parameter f_4 from Eq. (15) is chosen in order to include the largest error at the boundary of the range change.

The accuracy of digital display radiometers is influenced by the relative accuracy error of reading and the quantization error (in general ± 1 digit). Accordingly, the parameter f_4 is given by Eq. (17),

$$f_4 = \left|f_{\text{display}}\right| + \frac{k}{P_{\max}} \cdot |d|, \tag{17}$$

where

f_{display}	relative accuracy error of reading, in %
k	factor for range changing according to Eq. (16)
$P_{\max}$	the number of different output codes possible (e.g. for a 3 1/2 digit display, $P_{\max}$ = 1,999)
D	quantization error.

4.8 Fatigue

4.8.1 General

Fatigue is the reversible temporal change in the responsivity, under constant operating conditions, caused by incident irradiance.

NOTE: During the operation of radiometers, reversible changes can occur *in the responsivity as well as in the spectral responsivity. These changes are designated fatigue. Fatigue is generally greater for higher detector irradiation levels.*

4.8.2 Measurement

Fatigue should be measured with temporary stable irradiation at a level close to the highest measurable one.

The source used and the specific radiometric quantity shall be stated. The operating conditions (ambient temperature, supply voltage, etc.) should be held constant. The output signal should be measured as a function of the irradiation period. Before performing the test, the radiometer head should not be exposed to radiation for at least 24 hours.

4.8.3 Characterisation

For showing the fatigue, the function of systematic deviation $f_5(t)$ is given according to Eq. (18),

$$f_5(t) = \frac{Y(t)}{Y(t_0)} - 1\,, \qquad (18)$$

where

t	elapsed time since the beginning of illuminating the radiometer head with the constant irradiance
$Y(t)$	output signal at time t
t_0	reference time, e.g. 10 s.

For characterising, the characteristic f_5 according to Eq. (19) and the level of irradiance or radiance used for the test are to be stated,

$$f_5 = \frac{Y(30\,\mathrm{min})}{Y(10\,\mathrm{s})} - 1\,, \qquad (19)$$

where

Y(30 min)	output signal 30 minutes after the beginning of the irradiation
Y(10 s)	output signal 10 seconds after the beginning of the irradiation.

4.9 Temperature

4.9.1 General

Temperature dependence characterises the influence of the ambient temperature on the absolute responsivity and the relative spectral responsivity of the radiometer. If the radiometer is operated within an ambient temperature different from that used during calibration, measurement errors can occur.

4.9.2 Measurement

In order to measure a temperature dependence, the entire radiometer must be exposed to the desired temperature. The instrument must attain thermal equilibrium before starting the measurement.

> *NOTE: In general, it can be assumed that the radiometer will attain thermal equilibrium at the desired temperature in about one hour.*

In case there is a fatigue effect, the radiometer head should be irradiated only during the measurement. The measurement should be performed at least for ambient temperatures of 25°C (reference temperature) and 40°C. Radiometers which are used in the field should also be measured at an ambient temperature of 0°C. The measurement should be performed at an irradiation level on the radiometer head that approaches the largest value of an arbitrary measurement range.

4.9.3 Characterisation

Within the range of ambient temperature between T_1 and T_2 the temperature coefficient is defined according to Eq. (20),

$$\alpha(T_1, T_2) = \frac{Y(T_2) - Y(T_1)}{T_2 - T_1}, \tag{20}$$

where

T_1, T_2	range limits of ambient temperature
$Y(T_1)$	reading at the ambient temperature T_1
$Y(T_2)$	reading at the ambient temperature T_2.

> *NOTE: The temperature coefficient allows a correction of readings for other ambient temperature levels.*

The change of the output signal referred to the signal received at the ambient temperature of 25°C prescribed for calibration is used for characterising. For evaluating the characteristic f_6, a prescribed temperature difference ΔT is used according to Eq. (21) in conjunction with an upper temperature level of 40°C and a lower temperature level T, applicable for the measurement task,

$$f_6(T, \Delta T) = \left| \alpha(T, 40°\mathrm{C}) \cdot \frac{\Delta T}{Y(25°\mathrm{C})} \right|, \tag{21}$$

where:

T	ambient temperature level of 25°C with radiometers used for interior measurements or 0°C with radiometers also used for outdoor field measurements
ΔT	temperature difference, prescribed for different measurement tasks. For radiometers used in the laboratory a value of 2°C shall be used, otherwise a value of 10°C shall be used.

4.10 Modulated radiation

4.10.1 General

When measuring modulated radiation, the reading of a radiometer can deviate from the arithmetic mean value if the frequency of the modulated radiation is below the lower frequency limit, and if the peak overload capability is exceeded or if the settling time is not completed.

The range between the lower frequency limit f_{lo} and the upper frequency f_{up} of sinusoidal modulated radiation (modulation degree 1, see figure 2) is determined for a radiometer. Within this range the meter reading shall not differ more than 5 % from the reading for unmodulated radiation of the same arithmetic mean value.

The lower frequency limit f_{lo} of sinusoidal modulated radiation is the minimum frequency where the meter reading does not differ more than 5 % from the reading for unmodulated radiation of the same arithmetic mean.

The upper frequency limit f_{up} of sinusoidal modulated radiation is the maximum frequency where the meter reading does not differ more than 5 % from the reading for unmodulated radiation of the same arithmetic mean.

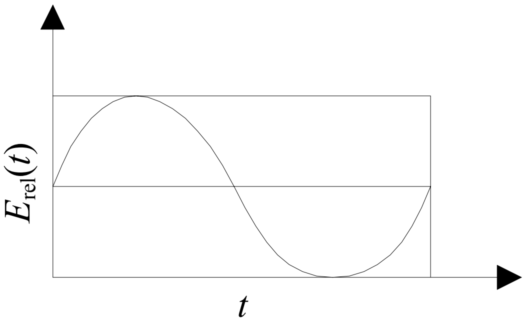

Figure 2. Sinusoidally modulated radiation of modulation degree 1.

4.10.2 Measurement

The measurement of the upper and lower frequency limits can be performed by means of a DC operated source and a rotating sector disc. A homogeneously irradiated acceptance area is not required.

> *NOTE 1: Suitable means must be employed to ensure that the arithmetic mean output of the radiation source used for the measurement remains constant when the modulation frequency is varied.*
>
> *NOTE 2: Experience shows that the generation of modulated radiation by means of a rotating sector disk in combination with a DC powered lamp can only be used for frequencies up to 10^4 Hz. Higher irradiances can be achieved by this method, however.*

The signal level for the measurement of modulated radiation must lead to a reading near the full scale of the used measuring range.

4.10.3 Characterisation

In order to show the function of systematic deviation $f_7(f)$ for modulated radiation versus the frequency, Eq. (22) is given,

$$f_7(f) = \left(\frac{Y(f)}{Y(f = 0\ \mathrm{Hz})} - 1 \right), \tag{22}$$

where

$Y(f = 0\ \mathrm{Hz})$ output signal for irradiation with unmodulated radiation

$Y(f)$ output signal for irradiation, modulated with frequency f, with the same arithmetic mean value as for steady-state irradiation.

To characterise the effect of modulated radiation, the characteristics f_7 (100 Hz) for 100 Hz, f_7 (f_{lo}) for the lower frequency limit and f_7 (f_{up}) for the upper frequency limit are used.

4.11 Polarisation

4.11.1 General

The output signal of a radiometer can depend on the polarisation condition of the measured radiation. In this case, the output signal Y changes when the linearly polarised quasiparallel incident radiation is rotated around the direction of incidence.

NOTE: Radiometer heads of irradiance meters may show polarisation dependence within certain angles of incidence.

4.11.2 Measurement

In order to measure the polarisation dependence, unpolarised radiation from a point source is required, following the measurement arrangement described in section 4.5.2.

NOTE: The radiation from a filament source is generally polarised. Depolarisation can be achieved by placing a silica plate, slightly tilted, in front of the radiation source. The position of the silica plate, in order to achieve complete depolarisation, is determined with the aid of a polarisation-independent detector (e.g. a windowless silicon planar photodiode perpendicular to the incident radiation) placed behind a polarisation filter.

To achieve complete depolarisation of the radiation (including the tilted glass plate), a polariser (e.g. two sheet polarisers placed back to back with their axes in parallel) is placed in front of the radiation source. The polariser can be rotated around the direction of incidence in order to change the position of the plane of polarisation.

NOTE: Using a second polariser, it has to be checked whether the first polariser is completely polarising the transmitted radiation.

The maximum $Y_{\max}$ and minimum $Y_{\min}$ output signals of the radiometer are then measured while rotating the first polariser. The measurements are to be carried out for at least two angles φ, which differ in 90°.

4.11.3 Characterisation

To characterise the polarisation dependence, the characteristic $f_8(\varepsilon)$ is given according to Eq. (23),

$$f_8(\varepsilon)=\frac{Y_{\max}(\varepsilon)-Y_{\min}(\varepsilon)}{Y_{\max}(\varepsilon)+Y_{\min}(\varepsilon)}. \tag{23}$$

To characterise the polarisation dependence, the characteristic f_8 is stated for an angle of incidence $\varepsilon = 30°$, $\varphi = 0°$

4.12 Spatial responsivity

4.12.1 General

The construction of some radiometer heads can lead to a significant non-uniform spatial responsivity over the acceptance area, including the relative spectral responsivity. With a uniform irradiation on the acceptance area, a non-uniform responsivity is without influence.

4.12.2 Measurement

For the measurement, a radiation source is arranged as described in section 4.5.2. A circular aperture with an inner diameter of 1/10, and an outer diameter of double the size of the acceptance area is placed in front of the radiometer head's acceptance area. Stray radiation should be avoided on the radiometer head.

The circular aperture has to be placed at five positions in front of the radiometer head's acceptance area as follows:

Position 1:	clear opening of the circular aperture centred in the middle.
Positions 2 to 5:	centre of clear opening of the circular aperture are placed at a point, which is located 2/3 along the radius from the centre of the acceptance area. The four positions (2 to 5) are at 90° intervals around the centre of the entrance aperture.

The output quantities Y_1 to Y_5 are to be measured at those five positions.

4.12.3 Characterisation

For characterising the influence of non-uniform irradiation on the acceptance area, the characteristic f_9 according to Eq. (24) is used,

$$f_9=\frac{\sum_{i=1}^{5}\left|Y_i-\overline{Y}\right|}{5\overline{Y}}, \tag{24}$$

where according to Eq. (25),

$$\overline{Y} = \frac{1}{5} \cdot \sum_{i=1}^{5} Y_i \,, \tag{25}$$

where

Y_i	output signal at one of the five positions on the acceptance area of the radiometer head with the input quantity X.

4.13 Range change

4.13.1 General

When changing the range of a radiometer to an adjacent range, a systematic deviation may occur.

NOTE: A deviation in case of range change is often due to careless calibration in the different ranges.

4.13.2 Measurement

For the measurement of the error arising from a range change, the irradiation on the radiometer head is to be adjusted to produce a reading of 90 % of full scale in the more sensitive range A.

The irradiation is then increased by a factor k [refer to Eq. (16)]. When increasing the irradiation, the range is changed to the less sensitive range B.

NOTE: For radiometers with a linear input - output characteristic (linearity of the radiometer), the signal can be simulated by a precision current source while the radiometer head is disconnected.

4.13.3 Characterisation

The error due to range change must be determined for each range. In order to characterise it, the characteristic f_{11} according to Eq. (26) is used,

$$f_{11} = \frac{Y_B}{k \cdot Y_A} - 1 \,, \tag{26}$$

where

Y_B	reading in the less sensitive range B with the input quantity X_B being k times as large as X_A
Y_A	reading range in the more sensitive range A with the input quantity X_A at about 90 % of full scale
K	factor according to Eq. (16)
X_A	input quantity creating the reading Y_A.

5 Instrument labelling

Beside the documentation of instrument characteristics as defined above, an appropriate "caution" or "warning" labelling shall be provided. This is because lamps and lamp systems that emit optical radiation within the UV may be health damaging. Within the documentation identification of precautions that could be taken to avoid risks shall be mentioned. For example, information on shielding or a warning against staring at a particular source.

6 Instrument classification

A classification of UV-meters shall depend on the uncertainty of spectral response, since it influences the measurement most. To classify a UV-meter the $f_1(Z)$ criteria should be applied, using the light sources defined with their spectral distributions in Table (1) in the Appendix. The groups are classified with:

$f_1(Z)_{\max} \leq 20\%$ as Class A

$f_1(Z)_{\max} \leq 40\%$ as Class B

$f_1(Z)_{\max} \leq 70\%$ as Class C

Radiometers with an $f_1(Z)_{\max} \geq 70\ \%$ are not useable in general.

Note, however, that for a specific light source a generally unusable UV-radiometer could conceivably be of the best class (within 20 %).

Manufacturer can add his own lamp and give classification for this lamp.

7 Literature

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CEN/TC169/WG8	Incoherent optical radiation – Measurement and assessment of radiation exposures by artificial UV-sources in the workplace, Draft.
Krochmann, J. Reismann, K.	Über den Spektralangleich von Strahlungsempfängern und von Lichtquellen, *Optik* **56(**1), 83-93 (1980).
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