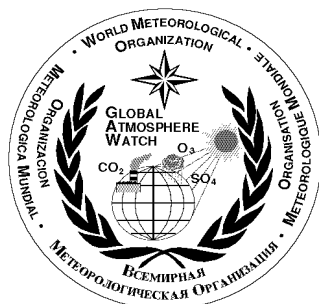


WORLD METEOROLOGICAL ORGANIZATION GLOBAL ATMOSPHERE WATCH



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Instruments to measure solar ultraviolet radiation

Part 1: Spectral instruments

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PREFACE

The WMO Executive Council, through actions initiated by the EC Panel of Experts/CAS Working Group on Environmental Pollution and Atmospheric Chemistry, has placed high priority on improving the quality and availability of the Global Atmosphere Watch (GAW) measurements. In order to address these needs and requirements for ultraviolet (UV) radiation, the WMO/GAW Scientific Advisory Group (SAG) for UV was established in 1995 to develop and implement the Global UV Radiation Monitoring Network in GAW. This includes drafting guidelines for instrument characterization, proposing standards for compatible observations, quality assurance and common calibration systems, data analysis and data archiving. The UV Monitoring and Assessment Program Panel (UMAP) co-sponsored the activities of the SAG for UV and this is gratefully acknowledged.

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The aim of this recommendation document (Instruments to measure solar ultraviolet radiation, Part 1: Spectral instruments) is to define instrument specifications and guidelines for instrument characterization, which are needed for reliable UV measurements. The document is part one of a series of several documents on UV measurements. This one is dedicated to spectral instruments only. The other parts of this series are currently in preparation and will address broadband and narrowband instruments. This report has been extensively discussed and reviewed by the UV SAG and its Working Group on Instrumentation. Further comments to this report are welcome.

The report must be considered a working document that will be updated and revised according to new scientific and technological developments. The report's main goal is to assist in harmonizing UV measurements.

Companion reports include the GAW report "Guidelines for Site Quality Control of UV Monitoring" and the "Guide to the WMO/GAW World Ultraviolet Radiation Data Centre (WUDC)", a manual on how to submit data to the WUDC.

The WMO acknowledges the great effort that has been put into this report, especially by the lead author Gunther Seckmeyer.

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1. INTRODUCTION

Solar ultraviolet (UV) radiation is known to have adverse effects on the biosphere including terrestrial and aquatic ecosystems as well as public health. As far as man is concerned, exposure to UV radiation from the sun is associated with skin cancer, accelerated ageing of the skin, cataract, or other eye diseases. It may also affect people's ability to resist infectious diseases, and compromise the effectiveness of vaccination. Several plants react to increased UV radiation with reduced growth or diminished photosynthetic activity. Phytoplankton, which is the first link in the maritime food chain, may be damaged as well.

As a consequence of the observed decline in stratospheric ozone concentration it is expected that UV levels will increase in high- and mid-latitudes. Apart from the inherent risk from solar UV radiation, life on earth therefore may be confronted with a further rise in UV. The anticorrelation between ozone and UV is usually partly masked by the variability in cloud cover, tropospheric pollution, or the aerosol content of the atmosphere. This fact complicates the assessment of UV trends and promotes measurements of solar UV because our ability to calculate UV radiation on Earth for cloudy conditions is still limited.

Thus, in order to quantify the current and future impact of solar UV radiation on the biosphere, highly accurate measurements of solar spectral UV irradiance are needed. However, these types of measurements are not simple. Difficulties arise from the steep decline of the solar spectrum in the UVB range that is caused by the absorption of atmospheric ozone. This decline leads to escalating uncertainties in the result of measurements if the specifications of the spectroradiometers used for this purpose do not meet specific requirements or if these instruments are not maintained appropriately.

The aim of this recommendation document drawn up by the ad hoc WMO Scientific Advisory Group (SAG) on UV Monitoring and its subgroup UV instrumentation is to define instrument specifications and guidelines for instrument characterization, which are needed for reliable UV measurements. The document is part one of a series of several documents on UV and UV measurements. This one is dedicated to spectral instruments only. The other parts of this series are currently in preparation and will discuss broadband and narrowband instruments.

The document is directed to scientists, companies, state organizations and funding agencies dealing with research and monitoring related to measurements of spectral UV irradiance. It should serve as a guide and is based on current experience and scientific knowledge about the measurement of UV radiation. This version of the document can be considered as the first edition. It is a working document and will evolve when new technologies or new objectives for UV spectroradiometry emerge. This may require an adjustment of the recommendations given. Readers are therefore encouraged to send comments and suggestions to the lead author (see address at the end of the document).

The document includes only the description of UV spectral instruments. Procedures for Quality Control (QC) are described in the WMO/GAW report *Guidelines for Site Quality Control of UV Monitoring* (WMO, 1998). A further document for Quality Assurance (QA) is in preparation. The data produced by UV instruments should be submitted to the WMO World Ultraviolet Radiation Data Centre (WUDC), operated on behalf of WMO by the Meteorological Service of Canada (MSC, former AES) in Toronto (A guide for submission can be found on the web at <http://www.tor.ec.gc.ca/woudc/woudc.htm> (Hare et al., 1998). Data has also been submitted to regional data centres such as the European UV database at <http://www.muk.uni-hannover.de/EDUCE> (Heikkilä et al., 1997)).

In section 2, two types of UV spectroradiometers (type S-1 and type S-2) are defined and their specifications are given, including remarks on how these specifications are connected to the scientific objectives of UV research. In section 3, guidelines for the characterization of UV spectroradiometers are compiled. In a comprehensive glossary at the end of the document all technical terms used in the document are defined or explained.

2. INSTRUMENTATION

2.1. General considerations

The specifications of UV instrumentation are based on the objectives of UV research. These include:

1. To establish a UV climatology by long-term monitoring, e.g. within a network of UV spectroradiometers
2. To detect trends, especially spectrally resolved trends, in global UV irradiance
3. To provide datasets for specific process studies and for the validation of radiative transfer models and/or satellite derived UV irradiance at the Earth's surface
4. To understand geographic differences in global spectral UV irradiance
5. To gain information about actual UV levels
6. To allow the determination of a UV index

Some of the objectives (e.g. trend detection) require high accuracy instruments with a superior long-term stability, because the expected magnitude of UV trends is rather small. In contrast, somewhat less demanding specifications are sufficient for instruments employed for the determination of erythemally weighted UV doses and hence the UV index. In this section, two types of instruments, type S-1 and type S-2, will be introduced. The specifications of type S-2 instruments are more rigid and consequently, the domain of these instruments is especially those measurements, where the highest accuracy is required. The required overall accuracy of type S-1 instruments is a little lower and a compromise between costs (hardware and operational) and scientific demands. However, type S-1 instruments are still extremely useful for UV monitoring and may also be employed for trend detection if trends are sufficiently large and QA/QC procedures are followed carefully. It is recommended that each instrument of either type is operated by at least one experienced full-time scientist or engineer.

Based on definitions and guidelines given below every operator of a spectroradiometric system should be able to specify the type (S-1 or S-2) of his instrument and to judge whether the instrument is suitable for the measurement task under consideration. For example, the operator might find out that his instrument essentially meets the specifications of a type S-2 instrument with the exception of a particular specification, which is not important for the objective of the measurement. As the science and technology evolves, instruments of other types are expected to be developed. However, at the time of writing this report, the two types mentioned are in existence.

The components of type S-1 and S-2 instruments are not prescribed, i.e., the choice between

- different entrance optics (e.g., diffuser or integrating sphere)
- set-up of the monochromator
- different detectors (e.g., photomultiplier or diode array)
- constant or variable scan speed
- different amplifier techniques (e.g., pulse counting, lock-in or analog)

is possible. The definition of the two types is based on the scientific needs defined by the different objectives of UV research, which in turn determine the desired overall accuracy of global spectral irradiance measurements. Therefore, the specifications introduced below are given in terms of instrument performance rather than instrument set-up. Some parameters, like wavelength accuracy, refer to the accuracy of the final data, which are derived from raw-data by post-processing. Thus, corrections may be applied (in fact, they are encouraged), to improve the accuracy of the result. These include for example:

- the improvement of wavelength alignment by correlation methods
- deconvolution algorithms to reduce or standardize the bandwidth
- cosine error correction methods to improve the accuracy of measured irradiance.

In the following, the characteristics of type S-1 and type S-2 instruments are introduced in more detail. Based on that, the required specifications for both types, as defined below in sections 2.1 and 2.2, are explained and reasons are given for the numbers chosen. Although some specifications are only relevant in the UVB range, specifications are not defined separately for the UVA and UVB, because most specifications, which can be met in the UVB, are easy to achieve in the UVA.

2.2. Detectability of UV Changes

A useful but ambitious goal is to attempt to detect a change in spectral UV irradiance resulting from a 1% change in total ozone column. The primary interest is in UV increases resulting from reductions in total ozone column. However, possible reductions in UV resulting from future recovery of the ozone layer,

or from a build up of tropospheric pollution (e.g., aerosols, ozone) or stratospheric particle loading may be relevant as well.

From past experience, it appears that the lowest calibration uncertainty that can be maintained for instruments designed to measure solar UV irradiance is currently limited to a few percent (e.g., $\pm 5\%$). Thus, to achieve the above goal, it will be necessary to include measurements at short wavelengths, where small changes in total ozone lead to relatively large changes in UV irradiance.

The spectral changes in UV resulting from a 1% ozone depletion have been calculated for overhead sun and for 70° solar zenith angle (SZA) (Madronich, 1993), (McKenzie et al., 1997). Percentage changes in UV increase rapidly at shorter wavelengths, but absolute changes decrease at wavelengths shorter than 310 nm. For overhead sun, a radiation change of 5% occurs at approximately 295 nm, when the absolute change in irradiance is approximately $10^{-4} \text{ W m}^{-2} \text{ nm}^{-1}$. At larger SZA, the condition for a 5% change in irradiance occurs at longer wavelengths. However, the corresponding absolute changes are even smaller, and thus more difficult to detect. It should be noted that high-sun observations are not always possible. For example, at high latitudes and in winter or spring, where ozone and UV changes are expected to be largest, the maximum SZA becomes large and can exceed 90° . These considerations show that given a calibration uncertainty of 5%, the increase in UV resulting from a 1% ozone depletion will be detectable only if the detection threshold is of the order of $10^{-6} \text{ W m}^{-2} \text{ nm}^{-1}$ or lower.

Uncertainties in the measurements of global spectral irradiance resulting from uncertainties in the wavelength alignment escalate at shorter wavelength. Therefore, in addition to the demands on calibration accuracy and detection threshold, an accurate wavelength alignment is required as well. For example, at 295 nm, a wavelength error of 0.1 nm corresponds to an irradiance error of approximately 9% for 30° solar zenith angle (see below).

In Figure 1, the change in global spectral irradiance due to a 1% and 3% decrease in total ozone column is compared with the uncertainty in spectral measurements arising from a 5% calibration uncertainty, a detection threshold of $10^{-6} \text{ W m}^{-2} \text{ nm}^{-1}$ and a wavelength error of 0.05 nm. For the calculation of spectral irradiance a SZA of 30° and a total ozone column of 300 DU was assumed. The steep increase of the uncertainty at 291 nm results from reaching the detection limit. The figure shows, that the percentage change in UV due to a 1% change in ozone only slightly exceeds the calculated measurement uncertainty at 295 nm. Thus, in order to detect a change of UV radiation caused by a 1% change in ozone, the wavelength alignment accuracy must be significantly better than $\pm 0.05 \text{ nm}$, the detection threshold must be in the order of $10^{-6} \text{ W m}^{-2} \text{ nm}^{-1}$ or lower and the accuracy of the absolute calibration must be at least $\pm 5\%$. These values form the basis for the specification of type S-2 instruments. However, it has to be emphasized that the observance of these specifications still does not guarantee that a trend caused by a 1% change in total ozone is detectable (Bernhard and Seckmeyer, 1999).

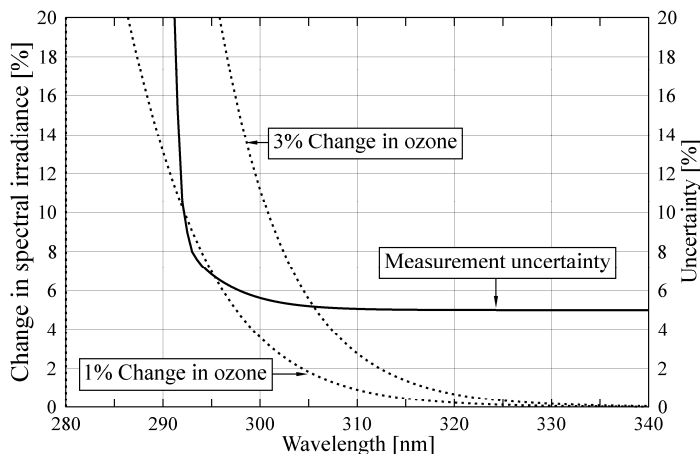


Figure 1: Percentage change in global spectral irradiance caused by a 1% and 3% change of total ozone compared with the uncertainty in spectral measurements arising from a 5% calibration

uncertainty, a wavelength error of 0.05 nm, and a detection threshold of $10^{-6} \text{ W m}^{-2} \text{ nm}^{-1}$. The change in irradiance was calculated for a solar zenith angle of 30° and a total ozone column of 300 DU.

For the validation of radiative transfer models the accuracy of spectral measurements must be comparable to the accuracy needed for trend detection. For the determination of actual UV levels and for the assessment and interpretation of geographical differences in global spectral UV irradiance the accuracy requirements are less demanding and thus these objectives are the main domain of type S-1 instruments.

In order to reach the required accuracy, S-1 and S-2 instruments should fulfil a variety of specifications in terms of instrument parameters, including the cosine error, the minimum spectral range, bandwidth, wavelength accuracy and precision, the sampling wavelength interval, instrument temperature stabilization, scan time, integration time and data collection frequency. The terms are defined in the glossary. In the following, further remarks on these parameters are given:

2.3. Instrumental Characteristics

Cosine error:

Entrance optics of many current spectroradiometers have a cosine error of about -10% at 60° incidence angle and of about -17% at 70° . At 350 nm, these instruments therefore underestimate global irradiance by about 7% to 13%, depending on solar elevation. For longer wavelength and larger solar zenith angles, the influence of the cosine error is even worse. In the UVB, errors in solar measurements that result from the cosine error depend less on solar elevation and variability in cloudiness because the proportion of direct to diffuse radiation is smaller in this spectral range. Nevertheless, errors in the measured irradiance may reach or exceed 10% in the UVB. Although appropriate correction procedures may lead to an improvement, uncertainties caused by the cosine error contribute significantly to the overall accuracy and are comparable to the uncertainties introduced by the irradiance or wavelength calibration. The application of correction procedures is limited, especially under conditions of broken clouds. Due to the accuracy requirements of S-2 instruments, the cosine error for this type should be smaller than $\pm 5\%$ for 60° incidence angle. If the radiation field is isotropic, errors in the measurement of spectral irradiance that arise from the deviation of the instrument's angular response from the ideal cosine should be below $\pm 5\%$ as well. A further reduction of the cosine error is desirable; more information about methods for cosine error correction is given in chapter 3.

Minimum spectral range:

Changes in UV due to ozone changes are significant mostly in the UVB range and are not detectable at wavelengths above 340 nm. If these ozone induced changes are to be detected against the background of changes due to other factors such as clouds and atmospheric aerosols it is advantageous to measure at wavelengths where the ozone absorption is negligible as well as in the UVB. The wavelength range 290 - 360 nm fulfils this requirement since there is almost no ozone absorption between 340 and 360 nm and this wavelength range may therefore be used for the detection of UV trends. However, the preferred recommendation for the wavelength range is 290 - 400 nm, which is also endorsed by the World Health Organization (WHO). Firstly, important biological weighting functions like the action spectrum for erythema proposed by CIE (McKinley and Diffey, 1987) include wavelengths up to 400 nm. In order to correctly calculate biologically effective radiation, spectral measurements extending to 400nm are therefore necessary. Secondly, since the Rayleigh scattering coefficient varies significantly in this wider wavelength range a more detailed investigation of the atmospheric radiative transfer is possible, allowing a better separation of the influence of ozone, atmospheric aerosols, clouds and Rayleigh scattering on UV irradiance.

Measurements over a wider wavelength range increase the time which is necessary to record a spectrum if the integration time of the spectroradiometer remains unchanged. Therefore, an extension of the wavelength range reduces either the number of spectra which can be recorded in a given time interval or the accuracy if the integration time is decreased. Because of the increased number of photons at longer wavelengths, shorter integration times can be used. The range 290-325 nm, defined as the minimum spectral range for type S-1 instruments, may be sufficient for specific purposes, e.g. ozone induced changes where short wavelengths have the greatest response (see Figure 1). However, for the objectives

to be studied with type S-2 instruments, the UVA part is essential and therefore measurements should be extended at least up to 360 nm, preferably 400 nm. Some researchers even consider an extension into the visible range to be desirable.

Bandwidth:

Generally, a smaller bandwidth allows a more accurate wavelength alignment and, in addition, systematic errors in the spectral irradiance arising from the steep increase of the solar UVB-spectrum at the Earth's surface become smaller. If no corrections for bandwidth are applied, this increase results in an overestimation of the measured global spectral irradiance: for an instrument with a triangular slit function of 1 nm FWHM, the contribution from the long wavelength wings of the slit causes the irradiance measured at 295 nm, 60° solar elevation and 320 DU to be increased by approximately 6.4%. At 300 nm, the respective increase is about 1.8%. On the other hand, a smaller bandwidth reduces the signal, usually in proportion to the square of the bandwidth, and thus leads to a lower signal-to-noise ratio. Therefore, the bandwidth setting of a spectroradiometer is a compromise between accuracy of wavelength alignment, systematic errors arising from the slope of the spectrum and the signal-to-noise ratio. Based on these considerations, it is recommended that the bandwidth is less than 1.0 nm FWHM for both instrument types.

Wavelength accuracy and precision:

Due to the steep increase in UVB towards longer wavelengths small uncertainties in the wavelength alignment of a spectroradiometer lead to pronounced uncertainties in the measured irradiance (Bais, 1997). For 60° solar elevation and a total ozone column of 300 DU, a wavelength uncertainty of 0.1 nm corresponds to irradiance uncertainty of approximately 9% and 5% at 295 nm and 300 nm, respectively. Similarly, a wavelength uncertainty of 0.1 nm corresponds to an uncertainty of the erythemally weighted irradiance of 2%. For these reasons the uncertainty of the wavelength alignment should be smaller than ± 0.1 nm. For the objectives investigated by type S-2 instruments, it should be smaller than 0.05 nm (see general considerations above).

Sampling wavelength interval:

The sampling wavelength interval is recommended to be significantly smaller than the bandwidth defined by the slit function of the spectroradiometer. The advantages of such an 'oversampling' are:

- a) Interpolation noise is reduced when spectra are aligned with a reference spectrum. This is particularly important when trace gas concentrations are derived from measurements of direct spectral irradiance using the method of differential optical absorption spectroscopy (DOAS) (Hofmann et al., 1995).
- b) Unknown features in the spectra can be unambiguously identified. Such unknowns could include sharp emission features in spectral calibration standards (e.g., tungsten halogen lamps of FEL type), or atmospheric pollutants. According to the sampling theorem (Brigham, 1974) a sampling interval less than 1/2 the highest frequency of interest is required. In hardware terms, the highest frequency observable is limited by the slit function, which in turn is limited by the resolving power of the spectrometer. For a given instrument, reductions in the slit function's FWHM are achieved only at the expense of throughput. Thus, it is sensible to at least match the sampling interval to the slit function. According to the sampling theorem, the sampling interval for a triangular bandpass should be less than 0.5 FWHM (Brigham, 1974).
- c) The determination of wavelength can be achieved more accurately (e.g., when scanning across a spectral line).

The disadvantages of oversampling are:

- a) Due to mechanical limitations, the scan time may take longer.
- b) Data storage requirements are increased.

Oversampling does not necessarily result in a lower Signal-to-Noise (SNR) ratio: if the total scan time remains the same and the sampling interval is reduced, the individual samples may have a poorer SNR. However, if the SNR is photon limited, the improvements can be achieved if necessary by filtering or averaging. In practice, the sample step will be a compromise: for type S-1 instruments a sampling wavelength interval of smaller than the bandwidth ($<1 \cdot \text{FWHM}$) is sufficient. Due to higher demands on the

wavelength accuracy of type S-2 instruments, a sampling wavelength interval of $< 0.5\text{-FWHM}$ appears to be advantageous. For DOAS applications, the sampling interval should be even smaller.

Instrument temperature:

Many spectroradiometers show a dependence of several instrument parameters (e.g., wavelength accuracy and spectral responsivity) on temperature. The instrument temperature should be sufficiently stable that the thresholds of the specified instrument parameters are not exceeded.

Scan time:

Ideally, all wavelengths of a spectrum should be measured simultaneously; otherwise the analysis of changing spectra gets unduly complicated. In practice, however, instrument requirements dictate that a spectrum is recorded sequentially in wavelength and the shortest and longest wavelength may be several minutes apart in time. An upper limit of 10 minutes is recommended only because it is achieved by many of the scanning spectroradiometers today. Faster instruments are desirable and may define new types.

Integration time:

The integration time for a measurement at a specific wavelength is not prescribed. In practice, the setting is a compromise between the requirements of a high signal-to-noise ratio and the desired short scan time of a spectrum. Therefore, it is not necessary to specify the integration time in addition to detection threshold and scan time.

Data frequency:

Ideally, it would be desirable to record as many spectra as possible. One scan per hour, as defined for type S-1 instrument, is the minimum frequency for spectral UV measurements in order to get an approximate overview of the diurnal pattern of global spectral irradiance. In order to accurately calculate the daily global spectral irradiation a much higher frequency is necessary, especially during cloudy conditions; during cloud-free days, a frequency of two spectra per hour leads to uncertainties in the calculated daily integrals of less than $\pm 1\%$. However, case studies show that for overcast situations, the same frequency can lead to uncertainties in the integrals of more than $\pm 10\%$. Therefore, it would be necessary for type S-2 instruments to set the sampling frequency to at least two spectra per hour, and, if possible to higher frequencies (e.g., four spectra per hour). For the investigation of cloud effects, it is advisable to take scans as often as possible.

2.4. Recommended specifications for Type S-1 instruments

Objectives

Instruments of this type are currently deployed around the world, they are commercially available from a number of manufactures and are extremely useful for monitoring UV levels. The quantity to be measured is global spectral irradiance in the UV.

The instruments are mainly used for:

- establishing a UV climatology
- informing the public about actual UV levels

In detail, the main objectives of type S-1 instruments are:

1. to establish a UV climatology by long-term monitoring, e.g., within a network of UV spectroradiometers, allowing for different types of instrumentation
2. to understand geographic differences in global spectral UV irradiance
3. to gain information about actual UV levels
4. to allow the determination of a UV index

Crucial to meeting these objectives is the availability of data from a wide range of instrumentation. The required overall accuracy of type S-1 instruments is a compromise between costs (hardware and operational) and scientific demands. For sufficiently large trends, type S-1 instruments may be used for trend detection if QA/QC procedures are followed carefully.

Recommended specifications

The definition of the following instrument specifications is based on the objectives for type S-1 instruments and the general considerations on instrument parameters given above. The instruments should be capable of all-weather, and automated operation. Essentially all quantities introduced in the table are defined in the glossary.

Quantity	Quality
Cosine error [§]	(a) < ±10 % for incidence angles <60° (b) < ±10 % to integrated isotropic radiance
Minimum spectral range	290 - 325 nm ⁺
Bandwidth (FWHM)	< 1 nm
Wavelength precision	< ±0.05 nm
Wavelength accuracy	< ±0.1 nm
Slit function	< 10 ⁻³ of maximum at 2.5·FWHM away from centre [#]
Sampling wavelength interval	< FWHM
Maximum irradiance	> 1 W m ⁻² nm ⁻¹ at 325 nm and, if applicable, 2 W m ⁻² nm ⁻¹ at 400 nm (noon maximum)
Detection threshold	< 5·10 ⁻⁵ W m ⁻² nm ⁻¹ (for SNR = 1 at 1 nm FWHM)
Stray light	< 5·10 ⁻⁴ W m ⁻² nm ⁻¹ when the instrument is exposed to the sun at minimum solar zenith angle
Instrument temperature	Monitored and sufficiently stable to maintain overall instrument stability
Scan time	< 10 minutes per spectrum, e.g., for ease of comparison
Overall calibration uncertainty [*]	< ±10% (unless limited by detection threshold)
Scan date and time	Recorded with each spectrum such that timing is known to within 10 seconds at each wavelength

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[§] smaller cosine errors would be desirable, but are unrealistic for the majority of the instruments that are currently in use. Definitions for cases (a) and (b) are given in the glossary.

^{*} the overall calibration uncertainty includes all uncertainties associated with the irradiance calibration (for example: uncertainty of the standard lamps, transfer uncertainties, alignment errors during calibration, and drift of the instrument between calibrations).

⁺ an extension to longer wavelengths is desirable for the establishment of an UV- climatology with respect to biological applications.

[#] For type S-2 instruments, the shape of the slit function is additionally specified at 6.0·FWHM away from the centre of the function. A similar specification is not included here, because of the limited spectral range of type S-1 instruments.

Ancillary measurements

In order to allow a better interpretation of the data, the measurements of global spectral irradiance should be supplemented by ancillary measurements.

- a) required:
 - Independent measurements of global irradiance insensitive to ozone absorption, e.g., measurements of short wave global irradiance with a pyranometer
- b) desirable
 - Direct normal spectral irradiance or diffuse spectral irradiance
 - Total ozone column, e.g., derived from measurements of direct normal spectral irradiance
 - Erythemally weighted irradiance, measured with a broad-band radiometer
 - Atmospheric pressure
 - Cloud amount
 - Illuminance, measured with a luxmeter
 - Direct irradiance at normal incidence measured with a pyrheliometer
 - Visibility

Data Frequency

The measurement schedule of type S-1 instruments should comprise at least one scan per hour and additionally a scan at local solar noon.

Data Processing

The post-processing of raw-data from S-1 instruments should comprise the following capabilities:

- Capability of cosine error corrections
- Capability of quantifying irradiance changes during a scan with a separate radiation sensor
- Extrapolation of UV irradiance for wavelengths > 325 nm if needed for the calculation of erythemally weighted irradiance, e.g., for the derivation of UV indices
- Retrieval of total ozone column

Instrument characterization

All calibration information and procedures should be clearly documented and archived at the observation site. The following instrument characterizations should be performed regularly; depending on the instrument, these checks may be needed even more frequently than recommended here:

- Daily:
 1. Dark current offset tests
 2. Check the input optics and clean if necessary
- Weekly/monthly:
 1. Test of the stability of the spectroradiometer's spectral responsivity
 2. Check of the wavelength alignment by correlation methods and/or by measurements of line spectra (e.g., with a low-pressure mercury lamp)
 3. Determination of the spectroradiometer's bandwidth
- Yearly (or as required)
 1. Calibration of working standards and reference standards (if necessary)
 2. Measurement of the angular response of the spectroradiometer with respect to incidence and azimuth angle
 3. Characterization of linearity and offsets
 4. Stray light tests

2.5. Recommended specifications for Type S-2 instruments

Objectives

Type S-2 instruments are mainly used for:

- the detection of spectrally resolved trends in global spectral UV irradiance
- specific process studies and for the validation of radiative transfer models and/or satellite derived UV irradiance at the Earth's surface
- the establishment of a UV climatology

Instruments satisfying the above purposes are generally not yet commercially available and represent the state-of-the-art in ongoing research and development. The quantity to be measured by S-2 instruments is global spectral irradiance in the UV. In addition, measurements of direct (normal or horizontal) spectral irradiance in the UV are encouraged, because these measurements are useful to investigate atmospheric processes like aerosol scattering.

In detail, the main objectives of type S-2 instruments are:

1. to understand the spectral consequence in the UV region of changing atmospheric composition (e.g., ozone, aerosols, clouds)
2. to understand geographic differences in global spectral UV irradiance
3. to monitor long term changes in UV irradiance
4. to make properly calibrated UV data available to the community

Recommended specifications

As described in Chapter 2, a useful but ambitious goal for type S-2 instruments is to attempt to detect a change in spectral UV irradiance resulting from a 1% change in total ozone column. The primary interest is in UV increases resulting from reductions in total ozone column. However, in this context, possible reductions in UV resulting from future recovery of the ozone layer, or from a build up of tropospheric pollution (e.g., aerosols, ozone) or stratospheric particle loading may be relevant as well. These considerations and the objectives listed above were proposed by the Network for the Detection of Stratospheric Change (NDSC) (McKenzie et al., 1997) and form the basis for the desired overall accuracy for type S-2 instruments, and, are also the basis for the following instrument specifications. The instruments should be capable of all-weather, and automated operation. In the glossary, definitions of all quantities introduced in the table are given.

Quantity	Quality
Cosine error [§]	(a) $< \pm 5\%$ for incidence angles $< 60^\circ$ (b) $< \pm 5\%$ to integrated isotropic radiance
Minimum spectral range	290 - 400 nm ⁺
Bandwidth (FWHM)	< 1 nm
Wavelength precision	$< \pm 0.03$ nm
Wavelength accuracy	$< \pm 0.05$ nm
Slit function	$< 10^{-3}$ of maximum at 2.5-FWHM away from centre $< 10^{-5}$ of maximum at 6.0-FWHM away from centre
Sampling wavelength interval	< 0.5 ·FWHM
Maximum irradiance	> 2 W m ⁻² nm ⁻¹ (noon maximum at 400 nm)
Detection threshold	$< 10^{-6}$ W m ⁻² nm ⁻¹ (for SNR = 1 at 1 nm FWHM)
Stray light	$< 10^{-6}$ W m ⁻² nm ⁻¹ (for SNR = 1 at 1 nm FWHM) when the instrument is exposed to the sun at minimum SZA
Instrument temperature	Monitored; typical temperature stability $< \pm 2$ °C to achieve a sufficient overall instrument stability
Scan time	< 10 minutes, e.g., for ease of comparison with models
Overall calibration uncertainty [*]	$< \pm 5\%$ (unless limited by threshold)
Scan date and time	Recorded with each spectrum so that timing is known to within 10 seconds at each wavelength

- § smaller cosine errors would be desirable, but are unrealistic for the majority of the instruments that are currently in use. Definitions for cases (a) and (b) are given in the glossary.
- * the overall calibration uncertainty includes all uncertainties associated with the irradiance calibration (for example: uncertainty of the standard lamps, transfer uncertainties, alignment errors during calibration, and drift of the instrument between calibrations).
- + for UV trend detection a smaller wavelength range e.g. 290-360 nm is likely to be sufficient, however, the larger wavelength range is required for many applications in biology, since biological weighting functions often include wavelengths higher than 360 nm (see page 5-7).

Ancillary measurements

In order to allow a better interpretation of the data, the measurements of spectral irradiance should be supplemented by ancillary measurements.

a) required

- Total ozone column, e.g., derived from direct normal spectral irradiance measurements
- Erythemally weighted irradiance, measured with a broad band radiometer
- Independent measurements of global irradiance insensitive to ozone absorption, e.g., measurements of short-wave global irradiance with a pyranometer

b) desirable

- Aerosol optical depth, e.g., derived from direct normal spectral irradiance measurements
- Atmospheric pressure
- Profiles of ozone
- Profiles of aerosols, e.g., derived from lidar or backscatter sondes
- Profiles of temperature, air pressure and relative humidity
- Trace gases (relevant for NDSC and other tropospheric measurements)
- Cloud amount
- Cloud images
- Illuminance, measured with a luxmeter
- Albedo

Data Frequency

The measurement schedule of type S-2 instruments should comprise sufficient scans to enable an accurate ($\pm 10\%$ uncertainty) daily integral of global spectral irradiance (i.e., daily global spectral irradiation) for days with no rain. If the spectra are sampled at fixed times, sufficient scans are needed to enable interpolation to fixed SZA for cloudless sky. Scans at local solar noon should be included.

Data Processing

The post-processing algorithms of raw-data from S-2 instruments should comprise the following capabilities:

- Capability of cosine error corrections
- Capability of quantifying irradiance changes during a scan with a separate UV sensor
- Retrieval of total ozone column from global spectral data

Instrument Characterization

All calibration information and procedures should be clearly documented and archived at the observation site. The following instrument characterizations should be performed regularly; depending on the instrument these checks may be needed even more frequently than recommended here:

- Daily:
 1. Dark current offset tests
 2. Check the input optics and clean if necessary
- Weekly/monthly:
 1. Test of the stability of the spectroradiometer's spectral responsivity
 2. Check of the wavelength alignment by correlation methods and/or by measurements of line spectra (e.g., with a low-pressure mercury lamp)
 3. Determination of the spectroradiometer's bandwidth
- Yearly (or as required)
 1. Calibration of working standards and reference standards (if necessary)
 2. Measurement of the angular response of the spectroradiometer with respect to incidence and azimuth angle including dependence on polarization, preferably in its upright position
 3. Characterization of linearity and offsets
 4. Stray light tests

3. GUIDELINES FOR INSTRUMENT CHARACTERIZATION

The following guidelines for instrument characterization represent methods that are currently used by the scientific community. They should be understood as suggestion for the user and should not be regarded as rules or standard methods. Additionally, it has to be emphasized that there may be many other methods for instrument characterization which may be equally suitable.

Tests of the stability of a spectroradiometer's spectral responsivity:

Tests are performed by regular (e.g., weekly) checks of the spectral responsivity with calibration lamps, i.e., working standards. The measured irradiance produced by the lamp should be compared with former measurements of the same lamp. To exclude the possibility that differences of the lamp measurements are attributable to changes of the working standard, the lamp has to be intercompared regularly with other lamps (see WMO, 1998).

Wavelength alignment:

1. **With the help of spectral lamps, e.g., low-pressure mercury lamps:**
 Several spectral lines are scanned by the spectroradiometer in small wavelength steps (e.g., 0.02 nm steps if the bandwidth of the spectroradiometer is 0.5 nm FWHM). The centre wavelength positions of the lines are determined and compared with an agreed wavelength scale (e.g., Lide, 1990). The internal wavelength scale of the spectroradiometer is changed in an appropriate way, e.g., by changing the relation between wavelength and step number of the spectroradiometer's stepper motor.

Remarks:

- a) The centre wavelength positions may be determined in the following ways:
 - i) By calculation of the centre of gravity wavelength λ_G of the spectral line:

$$\lambda_G = \frac{\int_{\text{spectral line}} \lambda \cdot E(\lambda) \cdot d\lambda}{\int_{\text{spectral line}} E(\lambda) \cdot d\lambda},$$

where $E(\lambda)$ is the measured spectral irradiance of the spectral line.

This method is only suitable for isolated lines which are not disturbed by the radiative continuum of the spectral lamp.

- ii) By fitting an appropriate function (e.g., triangle, parabola, Gaussian curve) to the measured spectral line. The wavelength at the maximum of the function is defined as the centre wavelength.
 - iii) It is not recommended to set the centre wavelength at the maximum of the measured line since its accuracy is limited by the sampling interval (e.g., 0.02 nm) and noise.
- b) If a mercury lamp is used, spectral lines with the following wavelengths are suitable (values are given in nm and related to air wavelengths): 253.652, 289.360, 296.728, 334.148, 404.656, 435.833. Apart from mercury lamps, cadmium, zinc, neon and thallium lamps are applicable.
 - c) Wavelength alignment must be carried out with the same bandwidth as for measurements of global spectral irradiance.
 - d) For spectroradiometers situated at the Earth's surface the wavelength scale should be referred to wavelengths in air at local pressure and temperature.
 - e) Wavelength alignment may be improved by correction algorithms, e.g. (Slaper et al., 1995). The specification of wavelength accuracy may therefore refer to the corrected data. However, a correction is appropriate only if the correction method works likewise for many atmospheric conditions.

2. By correlation with the Sun's Fraunhofer spectrum:

The Fraunhofer structure in a measured spectrum of global irradiance is compared with the same structure in a reference spectrum, e.g., an extraterrestrial spectrum. By shifting the wavelength scale of the measured spectrum the deviation of both spectra from each other are reduced and corrections for the wavelength alignment are calculated. Implementations of this method are described in (Slaper et al., 1995), (Huber et al., 1993) and (McKenzie et al., 1992).

Remarks:

- f) It is recommended that a careful wavelength alignment by means of spectral lamps is performed before the correlation method is applied, because uncertainties of reference spectra can be considerable.
- g) The accuracy of this method depends strongly on the wavelength accuracy of the reference spectrum used. Currently, the following extraterrestrial spectra are recommended for wavelength alignment: SUSIM/ATLAS3 (SUSIM/ATLAS3, 1994), McMath/Pierce (NSF/NOAO).
- h) Extraterrestrial spectra which refer to vacuum wavelength (e.g., SUSIM/ATLAS3) have to be shifted to air wavelengths.
- i) The accuracy of the correlation method can be limited by drifting clouds.

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Determination of the slit function:

The usual method for the determination of a spectroradiometer's slit function consists of scanning a monochromatic radiation source (e.g., a selected line from either a low-pressure mercury lamp or a laser) by the spectroradiometer with the scanning range centered at the wavelength of the source. The slit function is then the spectral mirror-image of the recorded spectrum (Kostkowski, 1979) with the mirror plane at the wavelength of the incident radiation.

Remarks:

- a) It is assumed that the wavelength alignment of the spectroradiometer is perfect, i.e., the wavelength of the incident radiation equals the centre wavelength of the slit function. In this context it is recommended to fully illuminate the entrance slit by an appropriate design of the input optics.
- b) The slit function should be normalized to 1 at the wavelength of the incident radiation.
- c) Since the slit function of a spectroradiometer may be wavelength dependent, it should be determined at several centre wavelengths in the UV.
- d) A laser (e.g., a Helium-Cadmium laser operating at 325 nm) rather than a mercury lamp is recommended for the determination of the slit function, since the laser line is much less disturbed by a radiation continuum or other spectral lines than a mercury lamp. With a laser the slit function can be measured over more than five orders of magnitude, whereas with the 253.652 nm line of a

mercury lamp the range is limited by the continuum radiation of the lamp below 10^{-3} to 10^{-4} of the peak value.

- e) Since some lasers include radiation at wavelengths other than the primary laser line, filters or dispersive devices may be necessary to select the laser line (Kostkowski, 1979).
- f) The method described is accurate only if the factors affecting the shape of the slit function (e.g., dispersion, scattering) change negligibly over the entire wavelength range of the function (Kostkowski, 1979).
- g) The method described is an indirect method. For this reason, the measurement has to be mirrored to form the slit function. The direct method for the determination of the slit function requires a tuneable radiation source. The direct method is problematic since tuneable radiation sources in the UV of sufficient power are presently not available. In this method, a spectroradiometer with fixed wavelength setting is irradiated with a monochromatic beam whose wavelength is varied over the wavelength range for which the magnitude of the radiometer's spectral responsivity is not zero (Kostkowski, 1979). The spectral irradiance measured by the radiometer at the different wavelengths of the source represents the slit function.

Determination of the bandwidth:

The bandwidth is determined from measurements of spectral lines, e.g., from a low-pressure mercury lamp or a laser.

Remarks:

- a) Since bandwidth may be wavelength dependent, it should be determined at several wavelengths in the UV.
- b) A suitable laser is a Helium-Cadmium laser operating at 325 nm.

Determination of the spectral responsivity $s(\lambda)$:

The signal of a spectroradiometer while scanning a calibration lamp (e.g., a working standard) is recorded and divided by the spectral irradiance which is produced by the lamp at the place of the radiometer's entrance optics and stated in the lamp's certificate.

Remarks:

- a) The determination of the spectral responsivity is often denoted as irradiance calibration of a radiometer.
- b) The prescribed conditions for the determination of the spectral responsivity should be stated in the lamp's certificate and must be followed. These include:
 - i) The distance between lamp and the reference plane of the spectroradiometer's entrance optics, which is a critical parameter. For a flat diffuser, the reference plane is usually the front surface of the diffuser. For an integrating sphere, the reference plane normally lies in the entrance aperture of the sphere. For curved diffusers, the determination of the reference plane is more difficult; an appropriate method to determine the plane is given in (Bernhard and Seckmeyer, 1997).
 - ii) The alignment of the lamp and entrance optics.
 - iii) The orientation of the lamp (e.g., horizontally or vertically).
 - iv) The direction of the lamp current.
 - v) The lamp current. This should be monitored by the voltage drop across a precision resistor (shunt) calibrated by a standard laboratory. For type S-1 instruments the current should have a relative precision of 10^{-4} and a relative accuracy of 10^{-3} ; for type S-2 instruments the current should have a relative precision of 10^{-5} and a relative accuracy of 10^{-4} . Shunts and precision voltmeters to measure the voltage drop should be recalibrated at least every two years.
 - vi) Room temperature
 - vii) The voltage drop across the lamp should be monitored.
- c) The observance of the lamp current is crucial because variations in the lamp current of 1% result in UV irradiance variations exceeding 10%.
- d) Since irradiance values stated in calibration certificates of standard lamps are often given in steps of 5 to 20 nm, wavelengths in between should be calculated by an appropriate interpolation (e.g.,

spline or Langrangian interpolation). Linear interpolation may lead to errors exceeding 4%. Additional errors may arise from sharp emission features in lamp spectra (sometimes, such features can even be observed in spectra of tungsten halogen lamps).

- e) Stray light in the laboratory should be diminished as much as possible, e.g., by appropriate baffles and use of a darkroom.
- f) The global spectral irradiance is then determined by dividing the signal of the spectroradiometer when measuring solar radiation by $s(\lambda)$. Appropriate corrections (e.g., for non-linearities and cosine errors) may then have to be applied.
- g) When possible, the spectral responsivity should be determined at the place where the measurement of global spectral irradiance is performed. This avoids uncertainties due to changes in $s(\lambda)$ that may result from transportation of the spectroradiometer.

Calibration of working standards:

Working standards are calibrated against a reference standard. In a first step, the spectral responsivity of a spectroradiometer has to be determined by the methods described above using the reference standard. In a second step, the signal of the spectroradiometer when measuring the working standard is divided by the spectral responsivity to derive the spectral irradiance produced by the working standard.

Remarks:

- a) It is recommended to check the stability of the spectroradiometer by measurement of an additional standard before and after the calibration of working standards.
- b) Calibration standards, either reference standards or working standards, should be recalibrated (or replaced) after 20 hours of use, unless otherwise stated in the lamp's certificate. A recalibration of reference standards should be performed by standard laboratories.
- c) A calibration certificate for each working standard should be prepared including irradiance values and conditions during calibration.
- d) The calibration of working standards should be traceable back to national standard laboratories (e.g., NIST, NPL, PTB) in no more than two steps since for each further step the uncertainty of the irradiance scale may escalate.
- e) The noise in the spectra of working standards can be reduced by smoothing but great care has to be taken because instrument features or emission lines of the lamps can affect the accuracy of the calibration.

Measurement of the angular response:

The angular response of a spectroradiometer may be measured (1) by moving a lamp around the radiometer or (2) by turning the radiometer around a fixed lamp. For both methods, the dependence of the spectroradiometer's signal is measured with respect to the incidence angle ε and the azimuth angle φ . Method (1) is recommended only if it can be assured that the movement of the lamp does not influence its output. Method (2) is only recommended if the turning of the instrument does not influence its sensitivity.

Remarks:

- a) The angular response of the input optics should be reliably characterized in the laboratory to the extent that the cosine error can also be known with confidence when the instrument is deployed at the measuring site. The measurement system must therefore ensure that repeatable results are obtained when the instrument is removed and replaced, and that the orientation of the receiving surface can be reliably transferred from the laboratory to the measuring site.
- b) The measurements should be made
 - i) at incidence angles ε between 0° and 85° in steps no larger than 5° ,
 - ii) at least at two wavelengths covering the spectral range of the instrument and at more wavelengths if these results indicate that this is necessary.
 - iii) in at least two azimuth planes.

- c) Azimuthal dependencies of the entrance optics should be avoided as much as possible because resulting errors are difficult to correct.
- d) The equipment for determining the cosine error should be designed such that an uncertainty of less than 0.2° can be maintained for all incidence angles (at 85° incidence angle, an angular uncertainty of $\pm 0.2^\circ$ already gives an uncertainty in angular response of $\pm 4\%$.)

Characterization of the entrance optics:

Apart from the angular response, the characterization of the entrance optics should include

- a) transmission
- b) weather durability
- c) ageing with respect to transmission and angular response
- d) fluorescence of the diffusing material
- e) tests of the polarization dependence either with respect to angular response or spectral responsivity

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A more detailed description of the appropriate methods may be found in (Bernhard and Seckmeyer, 1997).

Determination of linearity:

The linearity may be measured using a variety of methods. A comprehensive summary can be found in (Budde, 1983). In the following, two methods based on the inverse square law and the 'beam addition method' are briefly described. Both methods can be recommended.

1. The inverse square law method (Budde, 1983):

This method is based on the fact that the irradiance produced by a point source is inversely proportional to the square of the distance r . For testing the linearity, the irradiances E_1 and E_2 produced by the source are measured for two different distances r_1 and r_2 . For linearity of response it follows that:

$$\frac{E_1}{E_2} = \left(\frac{r_2^2}{r_1^2} \right)$$

Deviations from this relation quantify the non-linearity.

Remarks:

- a) Since real lamps are not point sources, the minimum distance r must be at least ten times the dimension of the lamp.
- b) For measuring linearity over several orders of magnitude, repetitions of measurements for a number of source levels may be necessary.
- c) The expression $f_3(Y)$ quantifies the correction for non-linearity to be applied to measured irradiance

$$f_3(Y) = \frac{Y_{\text{read}}}{Y_{\text{read,K}}} \cdot \frac{E_K}{E} - 1$$

where Y_{read} is the reading of the radiometer
 $Y_{\text{read,K}}$ is the reading at the calibration level
 E is the irradiance at the reading Y_{read}
 and E_K is the irradiance at the reading $Y_{\text{read,K}}$

- d) A similar technique can be used to determine the reference plane of entrance optics (see Bernhard and Seckmeyer, 1997).

2. The beam addition method:

By this method, a beam from a radiation source is split into two paths. Both paths are variably attenuated, recombined and finally measured by the radiometer under test. By means of shutters for each path, the contribution from each radiation path to the combined beam is measured separately, as is the combined beam with all shutters open. Repetitions of such sets of measurements for a number of source levels permit the evaluation of linearity. An automated linearity tester based on this method is described in (Saunders and Shumaker, 1984).

Determination of the dark current offset:

The dark current offset is measured by recording the spectroradiometer's detector signal if no radiation is falling on it. The light path may be blocked by a shutter in the monochromator. Alternatively, the offset may be recorded at a wavelength below the detection threshold of the spectroradiometer (e.g., below 280 nm for solar measurements).

Stray light tests:

Stray light tests may be performed (1) using the cut-off of the solar spectrum in the UVB range which is caused by atmospheric ozone or (2) with the help of cut-off filters at wavelengths below their cut-off points (CIE, 1984). Method (1) has the advantage that stray light is determined in the spectral range of primary interest. With cut-off filters, additionally the spectral distribution of the stray light can be roughly determined (CIE, 1984). With both methods, stray light becomes apparent if the measured spectral irradiance deviates from the slope pre-determined by the filter.

Remarks:

- a) Stray light figures which are given by instrument manufactures and which are based on isolated laser lines may not be applicable for solar measurements.
- b) For instruments using fiber optics, a sensitive method to detect stray light is to point to the sun with the end of the fiber, i.e., without any entrance optics attached to it. Thus, the sensitivity of the instrument may be enhanced by a factor of more than 100, compared to using a cosine diffuser. As a consequence, a stray light test becomes more sensitive by over two orders of magnitude.
- c) The way the amount of stray light is quantified in this document is described in the glossary.

Cosine error correction:

Methods for the correction of the cosine error must take into consideration (1) the deviation of the directional response of the spectroradiometer from the ideal cosine response and (2) the distribution of the radiation field, i.e., the distribution of radiance, when measuring solar radiation. Because the radiation field is generally not known in detail, approximations have to be made. The most common approximations and simplifications are:

- a) The global spectral irradiance is defined as the sum of direct horizontal spectral irradiance and diffuse spectral irradiance. For clear-sky conditions, the proportion of both can be either measured directly or calculated by a model. For overcast conditions, the direct spectral irradiance is set to zero. For partly cloudy conditions, the accuracy of cosine error correction methods is generally limited.
- b) The directional distribution of sky radiance is regarded as isotropic. This assumption has proved to be approximately valid in the UVB (Blumthaler et al., 1996).

Methods of cosine error corrections should provide estimates of their uncertainty. Description of implementations and validations of cosine error correction algorithms can be found in (Bernhard and Seckmeyer, 1997), (Seckmeyer and Bernhard, 1993), (Gröbner et al., 1996), (McKenzie et al., 1992), (Feister et al., 1997), and (Bais et al., 1998).

GLOSSARY

Accuracy:

The closeness of agreement between test result and the accepted reference value (ISO, 1994).

Remarks:

- a) The test result is a value of the quantity to be measured by completely carrying out a specified measurement method, once.
- b) The accepted reference value is a value that serves as an agreed-upon reference for comparison, and which is derived as (i) a theoretical or established value, based on scientific principles, (ii) an assigned or certified value, based on experimental work of some national or international organization, or (iii) a consensus or certified value, based on collaborative experimental work under the auspices of a scientific or engineering group.
- c) Wavelength accuracy of a spectroradiometer is the closeness of agreement between the measured positions of a spectral line and the agreed actual position of the line (e.g., Lide, 1990).

Aerosol optical depth:

Quantity expressing the attenuation of the solar beam passing through the Earth's atmosphere due to Aerosols (see (Iqbal, 1983) for details):

$$T_a(\lambda) = e^{-\tau_a(\lambda)m}$$

where $T_a(\lambda)$ is the transmittance of the aerosol layer
 $\tau_a(\lambda)$ is the aerosol optical depth
 m is the relative optical air mass at actual pressure

Albedo:

Reflectance a of the Earth's surface, irradiated by sun and sky radiation:

$$a = \frac{M_G}{E_G}$$

where E_G is the short-wave global irradiance
 M_G is the radiant exitance of the Earth's surface, i.e., the ratio between the radiant power Φ reflected from the surface in the wavelength range 0.3 μm - 3 μm and the area A of the surface

Remarks:

- a) The albedo can be measured with two radiometers with cosine weighted field-of-view in about 2 m - 4 m height above the ground.
- b) Since the albedo may vary considerably in the surroundings of the measurement site an average value within a radius of 30-40 km should be stated (Deguenther et al., 1998).
- c) Aircraft measurements of albedo are influenced by the backscattered radiation of the atmosphere below.
- d) In general, the albedo depends strongly on wavelength.

The definition of albedo given above is based on the terminology used in this document. Other definitions given in the literature may be applicable as well. In (Iqbal, 1983), the albedo is very generally defined as the ratio of radiation reflected from a surface to the radiation incident on that surface, whereas in

other meteorological publications the term albedo sometimes includes the radiation that is thermally emitted by the surface.

Bandwidth:

Full width at half maximum (FWHM) of a spectroradiometer’s slit function, usually expressed in nm.

Biological weighting function or action spectrum:

Function to describe the wavelength dependence of effects introduced by electromagnetic radiation on biological matter. Depending on the effect and the involved organism different biological weighting functions $W(\lambda)$ are used. The biologically effective irradiance $E_{weighted}$ is calculated by multiplying the global spectral irradiance $E_G(\lambda)$ with the action spectrum $W(\lambda)$ and integrating over wavelength λ :

$$E_{weighted} = \int E_G(\lambda) \cdot W(\lambda) d\lambda$$

An important weighting function is the action spectrum for erythema proposed by CIE (McKinley and Diffey, 1987), which describes the wavelength dependence of the reddening of human skin by UV radiation (see also below ‘erythemally weighted irradiance E_{CIE} ‘). Another important example is the action spectrum for DNA damage.

Cosine error:

The deviation of the angular response of a radiometer from the ideal cosine response is specified with two parameters in this document. The first of these (a) is defined according to (CIE, 1982) and is expressed by the quantity $f_2(\varepsilon, \varphi)$:

$$f_2(\varepsilon, \varphi) = \left(\frac{Y_{reading}(\varepsilon, \varphi)}{Y_{reading}(\varepsilon = 0^\circ, \varphi) \cos(\varepsilon)} - 1 \right) \times 100\%$$

- where ε is the incidence angle of the radiation
- φ is the azimuth angle
- $Y_{reading}(\varepsilon, \varphi)$ is the reading of the radiometer at angles ε and φ
- $Y_{reading}(\varepsilon = 0^\circ, \varphi) \cos(\varepsilon)$ is the ideal response

The second specification (b) refers to isotropic radiation and is defined as follows:

$$f'_2(\varepsilon, \varphi) = \left(\frac{\int_0^{2\pi} \int_0^{\pi/2} Y_{reading}(\varepsilon, \varphi) / Y_{reading}(\varepsilon = 0^\circ, \varphi) \sin(\varepsilon) d\varepsilon d\varphi}{\int_0^{2\pi} \int_0^{\pi/2} \cos(\varepsilon) \sin(\varepsilon) d\varepsilon d\varphi} - 1 \right) \times 100\%$$

The cosine error may be wavelength dependent. In this case these quantities are becoming spectral quantities.

Dark current offset:

Signal of a detector or radiometer when no radiation is received by its sensitive area.

Deconvolution:

Deconvolution is a technique to account for the distortion in a measured spectrum caused by the finite bandwidth of the monochromator. By this technique, spectra with a particular bandwidth can be derived from spectra of the same source measured with a different bandwidth. An implementation of a deconvolution technique suitable for measurements of global spectral irradiance can be found in (Slaper et al., 1995).

Detection threshold:

Minimum spectral irradiance that is detectable. In the scope of this publication, the detection threshold corresponds to a Signal-to-Noise ratio of one.

Direct normal spectral irradiance $E_{\lambda,D}$:

Radiant energy dQ arriving from the disk of the sun per time interval dt , per wavelength interval $d\lambda$, and per area dA on a surface normal to the solar beam.

$$E_{\lambda,D} = \frac{dQ}{dt dA d\lambda}$$

Remark: The angular field of view of an instrument measuring direct normal spectral irradiance must be sufficiently small to reduce uncertainties caused by the circumsolar radiation. Recommendations for view-limiting geometries can be found in (WMO, 1983).

Diffuse spectral irradiance $E_{\lambda,S}$:

Radiant energy dQ arriving per time interval dt , per wavelength interval $d\lambda$, and per area dA on a horizontally oriented surface from all parts of the sky above the horizontal, **excluding** the disc of the sun.

$$E_{\lambda,S} = \frac{dQ}{dt dA d\lambda}$$

Erythemally weighted irradiance E_{CIE} :

Global spectral irradiance $E_G(\lambda)$ multiplied with the action spectrum for erythema, $C(\lambda)$, proposed by CIE (McKinley and Diffey, 1987), and integrated over wavelength λ :

$$E_{CIE} = \int_{250\text{nm}}^{400\text{nm}} E_G(\lambda) \cdot C(\lambda) d\lambda$$

Fatigue:

Fatigue is the reversible changing of the reading of a radiometer at constant input (e.g., global spectral irradiance), with other working conditions being constant (CIE, 1982).

Remark: Fatigue effects of the detector may be the first step of overloading.

Global spectral irradiance $E_{\lambda,G}$:

Radiant energy dQ arriving per time interval dt , per wavelength interval $d\lambda$, and per area dA on a horizontally oriented surface from all parts of the sky above the horizontal, including the disc of the sun itself:

$$E_{\lambda,G} = \frac{dQ}{dt dA d\lambda} = E_{\lambda,D} \cdot \cos(\vartheta) + E_{\lambda,S}$$

where ϑ is the solar zenith angle

Global spectral irradiation $H_{\lambda,G}$:

Global spectral irradiance $E_{\lambda,G}$, integrated over a certain time interval Δt .

$$H_{\lambda,G} = \int_{\Delta t} E_{\lambda,G} \cdot dt$$

Remark: Irradiation is often denoted as dose.

Linearity:

The linearity of a radiometer is the degree to which the output quantity of the radiometer (e.g., a current) is proportional to the input quantity (e.g., global spectral irradiance) (CIE, 1982).

Maximum irradiance:

Maximum spectral irradiance that can be measured with a spectroradiometer without overloading (saturating) of detector or amplifier.

Remark: Fatigue effects of the detector may be the first step of overloading.

Precision:

The closeness of agreement between independent test results obtained under stipulated conditions (ISO, 1994).

Remarks:

- a) The test result is a value of the quantity to be measured by completely carrying out a specified measurement method, once.
- b) Wavelength alignment precision of a spectroradiometer is the closeness of agreement between the results of several measurements of the position of a spectral line. The measurements have to be performed within a period of time comparable with the time interval between consecutive wavelength calibrations of the spectroradiometer.

Primary standard:

A standard that is designated or widely acknowledged as having the highest metrological quality. The value of a primary standard is accepted without reference to other standards of the same quantity (German Institute for Standardization, 1984).

Remark: For radiation measurements, primary standards are usually blackbodies or synchrotrons.

Process studies with respect to global spectral irradiance:

Studies which investigate the dependence of global spectral irradiance on the parameters by which it is influenced (e.g., total ozone column, aerosols, albedo).

Pyranometer :

Instrument for the measurement of short-wave irradiance, i.e., the radiant energy in the wavelength range $0.3 \mu\text{m} - 3 \mu\text{m}$ arriving per time interval dt , and per area dA on a plane surface.

Remark: If the surface is oriented horizontally, the pyranometer measures short-wave global irradiance.

Pyrheliometer:

Instrument for the measurement of short-wave direct solar irradiance, i.e., the radiant energy in the wavelength range $0.3 \mu\text{m} - 3 \mu\text{m}$ arriving from the disk of the sun per time interval dt , and per area dA on a plane surface normal to the solar beam.

Radiant energy:

Energy Q of the radiation.

Radiant power Φ :

Radiant energy dQ per time interval dt .

Reference standard:

A standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made are derived (German Institute for Standardization, 1984).

Remark: For radiation measurements, lamps which are supplied by national standard laboratories (e.g., NIST, NPL, PTB) are usually considered as reference standards.

Sampling wavelength interval:

Wavelength interval between subsequent measurements of a spectrum.

Signal-to-Noise ratio (SNR):

Ratio between the average reading \bar{Y} of a radiometer calculated from sufficient single measurements to the standard deviation σ_y of the readings of single measurements. For the determination of the SNR, all conditions (e.g., radiant energy received by the radiometer) have to remain unchanged.

$$\text{SNR} = \frac{\bar{Y}}{\sigma_y}$$

Remark: For the determination of the SNR, a 'single measurement' has to be recorded in the same manner, i.e., with the same integration time of the amplifiers, as during the normal operation of the radiometer.

Slit function:

Function which represents the relative spectral transmittance of a spectroradiometer as a function of wavelength for a given setting of wavelength λ_0 (CIE, 1984), (Kostkowski, 1979). The slit function should be normalized to 1 at λ_0 .

Remark: The slit function is sometimes denoted slit-scattering function.

Spectral responsivity $s(\lambda)$:

Quotient of the radiometer output $dY(\lambda)$ by the radiometer input $dX(\lambda)$ at wavelength λ (CIE, 1982):

$$s(\lambda) = \frac{dY(\lambda)}{dX(\lambda)}$$

Remarks:

- a) For measurement of global spectral irradiance the radiometer input $dX(\lambda)$ is $dE_{\lambda,G}$.
- b) The spectral responsivity may also be denoted spectral sensitivity.

Spectroradiometer:

Instrument for the spectrally resolved measurement of electromagnetic radiation.

Stray light:

Undesirable radiation with wavelengths *outside* the wavelength range of the slit function that is detected together with radiation *inside* this range by the detector of a spectroradiometer.

Remarks:

- a) The definition of stray light in this document is adjusted to the needs of solar UV measurements and is defined as apparent spectral global irradiance measured at a spectral range where no detectable radiation reaches the Earth's surface due to ozone absorption. For example, this is the case for wavelengths below 285 nm at low solar zenith angles. Therefore, if measurements of solar irradiance at 285 nm are above the noise level, say $1 \cdot 10^{-4} \text{ W}/(\text{m}^2 \text{ nm})$, the amount of stray light at 285 nm in the sense of this document is $1 \cdot 10^{-4} \text{ W}/(\text{m}^2 \text{ nm})$.
- b) The amount of stray light detected depends, amongst other factors, on wavelength, bandwidth, spectral response of the detector, spectral transmittance of the monochromator and all auxiliary optics, the spectral distribution from the source (CIE, 1984).
- c) The term "out-of-band (OOB) rejection" is sometimes used to address the same issue but its definition is different, although related to, stray light. The term out-of-band rejection is not used in this document.
- d) Stray light may be denoted as stray radiation.

Short-wave global irradiance E_G :

Radiant energy dQ in the wavelength range $0.3 \mu\text{m} - 3 \mu\text{m}$ arriving per time interval dt , and per area dA on a horizontally oriented surface from all parts of the sky above the horizontal, including the disc of the sun itself. The short-wave global irradiance is the global spectral irradiance integrated over the wavelength range $0.3 \mu\text{m} - 3 \mu\text{m}$.

Remark: In meteorology, short-wave global irradiance is usually denoted as global radiation (ISO, 1990). In order to avoid confusion between spectral and broad band quantities the term short-wave global irradiance is used throughout this document.

Total ozone column:

Height of a hypothetical layer which would result if all ozone molecules in a vertical column above the Earth's surface were brought to standard pressure (1013.25 hPa) and temperature (273.15 K). The total ozone column is usually reported in milli-atmosphere-centimeters (m-atm-cm), commonly called 'Dobson units' (DU).

One DU

- defines the amount of ozone in a vertical column which, when reduced to standard pressure and temperature, will occupy a depth of 0.01 mm
- corresponds to $2.69 \cdot 10^{16}$ molecules/cm²

Uncertainty:

A parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the quantity to be measured (German Institute for Standardization, 1984).

Remark: The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.

UV index:

A measure of solar UV radiation at the Earth's surface which is used for public information. According to (WMO, 1994) and (WMO, 1997), the UV index is calculated considering the following items:

1. Calculation of the erythemally weighted irradiance E_{CIE} (see above) by utilisation of the CIE action spectrum (McKinley and Diffey, 1987) normalized to 1.0 at 298 nm.
2. A minimum requirement is to report the daily maximum UV index (WMO, 1997).
3. The index is expressed by multiplying the weighted irradiance in Wm^{-2} by 40.0 (this will lead to an open-ended index which is normally between 0 and 16 at sea level, but with larger values possible at high altitudes).

Remarks:

- a) The definition of the UV index given above may be revised in future.
- b) According to the alternative definition given in (ICNIRP, 1995), the UV index is calculated as the daily maximum erythemally weighted irradiance in Watts per square meter, averaged over a duration of between 10 and 30 minutes and multiplied by 40.

UVA radiation:

Electromagnetic radiation between 315 and 400 nm (CIE, 1970).

UVB radiation:

Electromagnetic radiation between 280 and 315 nm (CIE, 1970).

Visibility:

Horizontal distance over which a prominent dark object can be clearly discerned against a contrasting background with the unaided eye (Huschke, 1959).

Remarks:

- a) The object should be black and either well ahead of the background or on the horizon.
- b) The visibility may be denoted *meteorological range* or *visual range*.

Wavelength alignment:

Assignment of a spectroradiometer's internal wavelengths scale (e.g., represented by the step number of the spectroradiometer's stepper motor) to an agreed wavelength scale, e.g., (Lide, 1990). The agreed wavelength scale may be represented by spectral lines of a low-pressure mercury lamp.

Remark: Wavelength alignment may also be denoted as wavelength calibration.

Working standard:

A standard that is used routinely to calibrate or check material measures, measuring instruments or reference materials. A working standard is usually calibrated against a reference standard (German Institute for Standardization, 1984).

Remark: For radiation measurements in the UV, working standards are usually based on tungsten halogen lamps and these lamps are finally used to calibrate radiometers. Working standards are the last part of the calibration chain which starts with the primary standard.

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