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Instruments to Measure Solar Ultraviolet Radiation  
Part 4: Array Spectroradiometers

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# WORLD METEOROLOGICAL ORGANIZATION GLOBAL ATMOSPHERE WATCH



No. 191

## Instruments to Measure Solar Ultraviolet Radiation

### Part 4: Array Spectroradiometers

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## 1. INTRODUCTION

Ultraviolet radiation from the sun causes a considerable global disease burden including acute and chronic health effects on the skin, eye and immune system. Worldwide up to 60,000 deaths a year are estimated to be caused by ultraviolet radiation, most of which are due to malignant melanoma (Lucas et.al, 2008). Much of the UV-related illness and death can be avoided through a series of simple prevention measures. On the other hand, some UV is essential for the production of vitamin D in people. Emerging evidence suggests an association between vitamin D levels as an indicator of health risk [WHO, 2008] relating to some cancers, cardiovascular disease and multiple sclerosis among others, along with the established link with musculo-skeletal health.

This paper is part four of a series of documents dedicated to instruments for the measurement of solar ultraviolet radiation. The series of documents has been drawn up by the WMO Scientific Advisory Group on UV Monitoring and the UV Instrumentation Subgroup. The aim of the series is to define instrument specifications and guidelines for instrument characterization that are needed for reliable UV measurements.

The documents are directed to scientists, instrument manufacturing companies, state organizations and funding agencies dealing with research and monitoring related to measurements of spectral UV irradiance. They should serve as guides and are 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 spectral instruments described in Part 1 of this series [Seckmeyer *et al.*, 2001] are able to separate the radiation into small wavelength bands with a typical resolution of 1 nm or less. Broadband instruments to measure erythemally-weighted UV radiation are described in Part 2 of this series [Seckmeyer *et al.*, 2005]. Part 3 describes multi-channel filter radiometers [Seckmeyer *et al.*, 2010], i.e. instruments providing signals that correspond to irradiance integrated over a number of discrete wavelength bands, typically with bandwidths of 1 to 10 nm full width at half maximum (FWHM) These instruments can be used to reconstruct the solar global spectral irradiance, or to derive specific products, such as erythemally weighted (or “sunburning”) irradiances, or estimates of total column ozone.

This document describes spectroradiometers for measuring UV radiation based on a different measurement principle: instead of rotating the grating to scan the spectrum across an exit slit onto a photomultiplier detector, in these instruments the spectrum of UV irradiance is imaged onto a detector consisting of many elements e.g., a diode array. Thus the entire spectral region of interest is measured at essentially the same time. This is the so-called multiplex advantage.

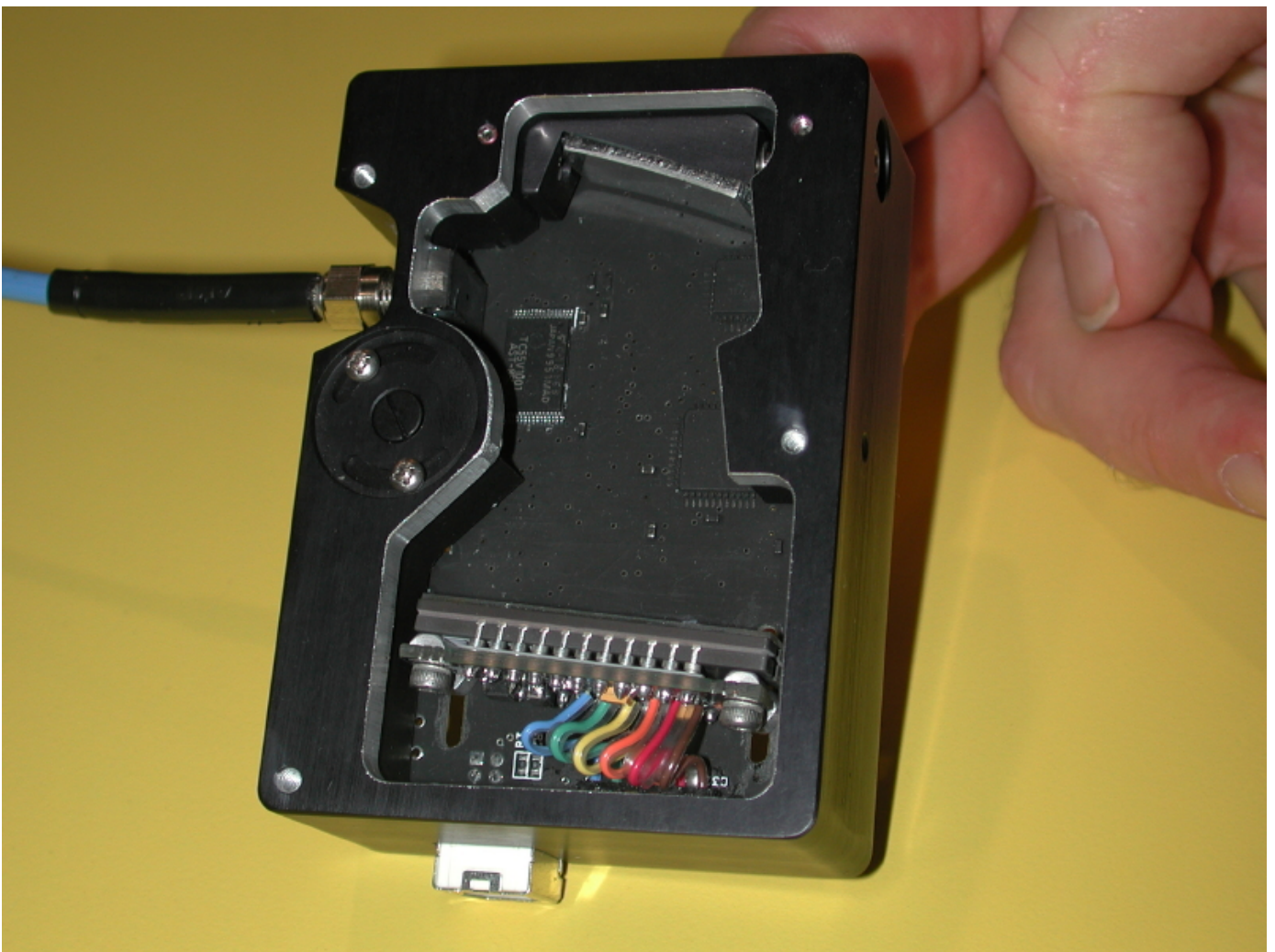
The major advantage of array spectroradiometers is their relatively fast detection of the spectrum. While scanning spectroradiometers (see Part 1 document of the series) typically measure a spectrum within several minutes, the array instruments are capable of measuring a spectrum within a second or faster. This enables new applications of these instruments, such as measuring spectral radiance or irradiance under changing conditions. Other advantages include: (1) portability that arises from their compact design, (2) stability and reliability that arises from having no moving parts, and (3) good stability of the photodiodes compared with photomultipliers.

For the measurement of solar UV radiation received at the Earth’s surface, the main disadvantage of array spectroradiometers is their inability to reduce stray light to an acceptable level. In conventional scanning instruments, the stray light problem can be reduced appreciably by the use of double dispersion. This option is not available in array instruments, and typically limits the lowest wavelength achievable to longer than 300 nm for solar measurements. Other disadvantages include: (1) the higher detection threshold of diode array spectroradiometers compared with scanning spectroradiometers using photomultipliers, and (2) the uncertainties

associated with the correction of the dark current, which may vary from diode to diode and is strongly temperature dependent.

In Section 2, the objectives for these instruments are given and discussed. In contrast to the Parts 1-3 of this series, there is no longer a restriction to irradiance measurements alone, and the objectives here are extended to three other physical quantities: actinic spectral irradiance, direct spectral irradiance and spectral radiance. These quantities may also be measured with scanning spectroradiometers (Part 1 of series), but such measurements were far less common and less in demand when that document was published 10 years ago.

In Section 3, the array spectroradiometers for the measurement of the above four physical UV quantities are defined and their specifications are given, including remarks on how these specifications are connected to the scientific objectives of UV research. In Section 4, guidelines for the characterization of array 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.



**Figure 1 - Typical array spectroradiometer. Usually array spectroradiometers are encapsulated and the optical parts cannot be seen. The cable on the left is an optical fibre for the optical input. The dispersion grating can be recognized on top and the detector array at the bottom of the monochromator**

## 2. OBJECTIVES

The required specifications of UV instrumentation discussed in this document depend on the objectives of the measurements. These include:

1. To study the short-term characteristics of spectral global and direct solar **irradiance**, e.g. in process studies on the impact of clouds and aerosols on UV irradiance.
2. To study the characteristics of spectral sky **radiance** as a function of zenith and azimuth angle, e.g. for process studies on the impact of clouds and aerosols on UV irradiance.
3. To study the characteristics of spectral **actinic irradiance** (sometimes called spectral scalar irradiance, or spectral actinic flux), e.g. in process studies on the impact of clouds and aerosols on UV irradiance.
4. To contribute to the development of a spectral UV climatology by long-term monitoring.
5. To understand geographic differences in spectral UV irradiance and radiance.
6. To understand temporal variations of spectrally resolved UV radiation quantities on different time scales.
7. To provide datasets for the validation of radiative transfer models and/or satellite derived UV irradiance at the Earth's surface.
8. To determine real-time UV levels, such as the UV Index (UVI).
9. To determine biologically weighted radiation quantities.

These instruments may also be used in applications such as the derivation of trace gas column density, trace gas profiles, aerosol optical properties, and the measurement of reflectance or transmission properties in the field.

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 some of the cases listed above, currently available array spectroradiometers cannot yet achieve the required performance specifications throughout the UV-B region.

To specify the array spectroradiometers the instruments are differentiated according to the following four measurement quantities:

- Global spectral irradiance.
- Actinic spectral irradiance.
- Direct spectral irradiance.
- Spectral radiance.

For each type of measurement a set of specifications is given in Section 3.

The definition of the four types is based on the scientific needs imposed by the different research objectives, which in turn are linked with the desired overall uncertainty of the radiation measurements. Therefore, the specifications introduced below are given in terms of instrument performance rather than instrument set-up. Some parameters, like the wavelength accuracy, refer to the accuracy of the final data, which are derived from raw-data by post-processing. Thus, corrections need to be applied, to reduce the uncertainty 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 global irradiance.
- Stray light correction, which is especially important for array spectrometers as they are single monochromators.

These array instruments – like the broadband instruments described in Part 2 of the series - are sometimes used to characterise the output of artificial UV sources such as sunbeds. For accurate radiative measurements of artificial sources, proper consideration of stray light issues is mandatory.

### 3. RECOMMENDED SPECIFICATIONS

	Global spectral irradiance	Actinic spectral irradiance	Direct spectral irradiance	Spectral radiance
Field of view	180°	360°	< 2°	< 5°
Angular response (a) For incidence angles (b) To integrated isotropic radiance (c) Azimuth error	Cosine error < ±5 % for angles <60° < ±5 % < ±3 %	Deviation < ±10 % for all angles < ±10 % < ± 3 %	Not applicable	Not applicable
Accuracy in positioning the optics	< 0.2° (levelling accuracy)	< 1° (levelling accuracy)	< 0.2°	< 1°
Maximum irradiance at 400 nm (noon)	> 2 W m <sup>-2</sup> nm <sup>-1</sup>	> 4 W m <sup>-2</sup> nm <sup>-1</sup>	> 2 W m <sup>-2</sup> nm <sup>-1</sup>	>1 W m <sup>-2</sup> nm <sup>-1</sup> sr <sup>-1</sup>
Detection threshold	< 10 <sup>-3</sup> W m <sup>-2</sup> nm <sup>-1</sup>			< 10 <sup>-3</sup> W m <sup>-2</sup> nm <sup>-1</sup> sr <sup>-1</sup>
Stray light (noon)	< 10 <sup>-3</sup> W m <sup>-2</sup> nm <sup>-1</sup>			< 10 <sup>-3</sup> W m <sup>-2</sup> nm <sup>-1</sup> sr <sup>-1</sup>
Typical spectral range	280 – 400 nm			
Bandwidth (FWHM)	< 1 nm			
Slit function	< 10 <sup>-3</sup> of maximum at 2.5 FWHM away from centre			
Sampling wavelength interval	< 0.2 FWHM (> 5 pixels/FWHM)			
Wavelength precision	< ±0.05 nm			
Wavelength accuracy	< ±0.1 nm			
Instrument temperature	Monitored and sufficiently stable to maintain overall instrument stability			
Frequency of recording spectra	> 0.1 Hz			
Overall calibration uncertainty	< ±10% (unless limited by detection threshold)			
Scan date and time	Recorded with each spectrum such that timing is known to within 1 s			
Nonlinearity	< 2 % for signals more than 50 times above detection threshold			

#### 3.1 Remarks on specifications

##### **Field of view (FOV)**

The angular response of radiometers to measure **global spectral irradiance** should vary with the cosine of the incidence angle. The response is therefore non-zero above the horizon, resulting in a field of view of 180°.

Radiometers for measuring **actinic spectral irradiance** should have a field of view of 360° to measure both upwelling and downwelling radiation. It should be noted that the required quantity “actinic spectral irradiance” does not represent the upwelling and downwelling irradiance on horizontal surfaces. When the UV albedo is small (i.e., at most snow-free locations), the upwelling component contributes typically less than 5% to the measurement. For these cases, a field of view of 180° (upper hemisphere) may be sufficient.

For **direct spectral irradiance** — when using a FOV smaller than 2° — more accurate tracking may be required for the derivation of optical properties such as aerosol optical depth, especially at shorter wavelengths [*Arola and Koskela, 2004*].

For **spectral radiance** — when using a FOV smaller than 2° — more accurate tracking may be required for trace gas profiling [*Frieß et al., 2006; Hönninger et al., 2004; Richter, 2006*].

### **Angular response**

**Global spectral irradiance entrance optics** of many spectroradiometers currently in use have a cosine error of about -5% at 60° incidence angle. These instruments underestimate global irradiance. Although appropriate correction procedures may lead to an improvement, uncertainties caused by the cosine error contribute significantly to the overall uncertainty and are comparable to the uncertainties introduced by the irradiance or wavelength calibration. Broken-cloud conditions present a particular challenge. It is therefore preferable to use input optics with cosine errors as small as possible.

For **actinic spectral irradiance entrance optics** that are currently available, angular response errors are typically of the order of 10%. Better entrance optics would be highly desirable because deviations at large incident angles lead to large uncertainties in the measured actinic irradiance.

Within this document we assume that for **direct spectral irradiance entrance optics** with a field of view of < 2° the radiance contribution from the area around the solar disk is negligible. Therefore, the specification of the angular response is noted as “not applicable” for direct spectral irradiance.

Similarly, the spectral radiance is assumed to be sufficiently homogeneous within the field of view of 5°. Therefore, the specification is also noted as “not applicable”. However, the input optics should measure radiation within the specified field of view only and the sensitivity outside the FOV should be negligible; thus the input optics need to be manufactured accordingly.

### **Accuracy in positioning the optics**

For global and actinic irradiance measurements the optics are fixed. But they should be accurately levelled at installation and checked regularly (see also Section 3.6). This can be accomplished, for example, with a spirit level attached to the optics. Incorrect levelling of global irradiance entrance optics can lead to significant uncertainties, especially at large solar zenith angles [*Seckmeyer et al., 2005*]. Incorrect levelling of actinic irradiance entrance optics should cause significantly smaller uncertainty due to their spherical design [e.g., *Wendisch et al., 2001*].

The azimuth and elevation angles for each spectral radiance measurement should be recorded.

### **Detection threshold**

In chapter 4 a description for determining the detection threshold can be found. The detection threshold shall be determined for the signal to noise ratio SNR = 1 at 1 nm FWHM. For several reasons (e.g., stray light, dynamic range, nonlinearities) the detection threshold of array instruments is higher than those of scanning spectroradiometers.

### **Stray light**

Stray light characterization and correction is of particular importance for the array instruments. There are various methods for stray light correction, described in Section 4 with their advantages and limitations.

### **Bandwidth**

Generally, a smaller bandwidth allows a more accurate wavelength assignment and, in addition, systematic errors in the spectral irradiance or radiance arising from the steep increase of the solar UV-B spectrum at the Earth’s surface become smaller. 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 300 nm, 60° solar elevation and 320 DU to be increased by about 2%. At shorter wavelengths this becomes more of an issue. On the other hand, a smaller bandwidth reduces the signal and thus leads to a lower signal-to-noise ratio. Therefore, the bandwidth setting of a spectroradiometer is a compromise between accuracy of wavelength assignment, 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 about 1 nm FWHM. But for some specific tasks (e.g., trace gas determination) it should be less. For array instruments the bandwidth usually varies across their operational spectral range. The wavelength assignment may be improved by post processing using deconvolution techniques (e.g., *Slaper et al.* 1995).

### **Slit function**

Although some instruments might not fulfil this specification, it is usually not the limiting factor for the uncertainty. In general far field stray light is more problematic.

### **Sampling wavelength interval**

Oversampling of the spectrum [*Hofmann et al.*, 1995] is required for assuring the accuracy in the wavelength registration, which is based on the determination of the slit function. 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 'oversampling' are:

- a) The correlation of measured to referenced spectra is improved. This is particularly important when trace gas concentrations are derived from measurements of spectral radiance or direct spectral irradiance using the method of differential optical absorption spectroscopy (DOAS) [e.g., *Camy-Peyret et al.*, 1996; *Hofmann et al.*, 1995; *Vandaele et al.*, 2005].
- b) Only by oversampling can unknown features in the spectra be unambiguously identified. Such unknowns could include sharp emission features in spectral calibration standards (e.g., tungsten halogen lamps of FEL type), or be the result of 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. According to the sampling theorem, the sampling interval for a triangular bandpass should be less than 0.5 FWHM. In practice the sampling interval should be less than 0.2 FWHM because of the problem that it is not possible to determine a slit function for each pixel.
- c) The determination of wavelength can be achieved more accurately (e.g., when measuring the signal of a spectral line).

### **Wavelength precision and accuracy**

Due to the steep increase of UV-B irradiance towards longer wavelengths, small uncertainties in wavelength assignment of a spectroradiometer lead to pronounced uncertainties in the measured irradiance. For array instruments, the wavelength corresponding to each element of the detector array is essentially fixed and determined by the geometry and characteristics (grating density and array size) of the spectrometer. It is therefore impossible to physically adjust the wavelength, and hence the effort centres on assigning the correct wavelength to each pixel.

Uncertainties in measurements of solar (ir)radiance resulting from wavelength uncertainties depend on wavelength, sun angle and total ozone column. For example, at 300 nm, the irradiance uncertainty arising from a wavelength uncertainty of  $\pm 0.1$  nm is  $\pm 6\%$  for a solar zenith angle of 40° and 320 DU [*Bernhard and Seckmeyer*, 1999]. Larger solar zenith angles and ozone amounts increase the slope of the solar spectrum and lead to even greater uncertainties. A wavelength accuracy of 0.1 nm ensures that its contribution to the overall uncertainty remains low. Variations in the wavelength assignment (i.e., the wavelength precision), which may for example be caused by changes in instrument temperature, should be smaller than  $\pm 0.05$  nm.

### ***Instrument temperature***

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

### ***Frequency for recording of spectra***

For many applications recording as many spectra as possible is desirable. However, the frequency for recording of spectra limits the time available for integration and signal averaging. In turn these limit the signal to noise ratio (SNR) which is connected to the detection threshold. SNR can be improved by applying longer integration times or by averaging spectra.

The following simple relationship applies:

Maximum data frequency =  $1 / (\text{Integration time} * \text{number of spectra} + \text{processing time})$

Many array instruments provide a function for signal averaging. The integration time of array spectroradiometers can usually be chosen between a few milliseconds and several seconds.

### ***Nonlinearity***

Uncertainties in linearity translate directly into uncertainties of measured quantities. For many array instruments nonlinearity effects are a serious concern.

## **3.2 Ancillary measurements, data processing and maintenance**

### ***Ancillary measurements***

The range of ancillary measurements depends on the data objectives for the measurements, but in general the more supporting data are available, the better. In order to allow a better interpretation of the data, the measurements of spectral radiance or irradiance should therefore be supplemented by ancillary measurements.

a) Recommended:

- 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 information.
- Illuminance, measured with a luxmeter.
- Direct irradiance at normal incidence measured with a pyrheliometer.
- Aerosol optical properties.
- Visibility.

### ***Data Frequency***

The data frequency depends on the integration time and on the purpose of the measurements. With data frequencies of about 0.1 Hz a huge amount of data is produced. Depending on the purpose of the measurements, longer averaging or integration times (e.g., one minute) for increasing the SNR or for reducing the data storage may be suitable. The specification just refers to the possibility to perform frequent measurements.

### **Data Processing**

The post-processing of raw-data should comprise the following capabilities:

- Dark current correction.
- Stray light corrections including their uncertainty.
- Cosine error correction (where applicable).
- Wavelength and bandwidth standardization.

Even after data processing it is important to retain the original logged data.

### **Instrument characterization**

All calibration information and procedures should be clearly documented and archived at the observations 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 measurements. Depending on instrument performance these measurements may be required more frequently, e.g., for each measurement.
  2. Check of the input optics and cleaning if necessary.
  3. Checking of sun tracking if applicable.
- 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.
  4. Checking of levelling of global irradiance optics.
- 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.

## **4. GUIDELINES FOR INSTRUMENT CHARACTERIZATION AND DATA CORRECTION**

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

### **Measurement of the angular response**

The angular response of a spectroradiometer may be measured (1) by rotating a lamp about the input aperture of radiometer or (2) by rotating the input optics relative to a fixed lamp. For both methods, the dependence of the spectroradiometer's signal is measured with respect to the incidence angle  $\varepsilon$  and the azimuth angle  $\varphi$ . Method (1) is recommended only if it can be assured that the movement of the lamp does not influence its output. Method (2) is recommended only 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  $\varepsilon$  between  $0^\circ$  and  $85^\circ$  in steps no larger than  $5^\circ$ ;
  - 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 far 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  $0.2^\circ$  can be maintained for all incidence angles (at  $85^\circ$  incidence angle, an angular uncertainty of  $\pm 0.2^\circ$  gives an uncertainty in angular response of  $\pm 4\%$ .)
- e) Illumination of the entrance optics must be homogeneous with an almost parallel beam and maintained as such irrespective of the incidence angle

### Characterization of the entrance optics

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

- a) Tests of weather durability.
- b) Tests of ageing with respect to transmission and angular response.
- c) Tests of fluorescence of the diffusing material.
- d) Tests of the polarization dependence either with respect to angular response or spectral responsivity.
- e) Determination of the field of view for radiance and direct irradiance measurements.
- f) Characterization of attenuation (or other) filters, if applicable.

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

### 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 must 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 UV-B [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 [Bais et al., 1998; Bernhard and Seckmeyer, 1997; Cordero et al., 2008; Feister et al., 1996; Gröbner et al., 1996; Hofzumahaus et al., 2004; McKenzie et al., 1992; Seckmeyer and Bernhard, 1993].

### 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 covering the entire operational spectral range.
- b) For the UV range, e.g. a Helium-Cadmium laser operating at 325 nm is suitable. However, other wavelengths may be needed. The ideal source for such measurements would be a tuneable laser.

### Determination of the dark current offset

The dark current is measured by recording the spectroradiometer's detector signal when no radiation is falling on it. For example, the measurement can take place during the night, or the light may be blocked by a shutter. Some operators determine the dark current by measuring signals at a wavelength below the detection threshold of the array spectroradiometer (e.g., below 250 nm). This is not recommended because the measured signal includes a stray light contribution which varies with wavelength and because dark current varies from pixel to pixel. The dark current depends on the temperature of the instrument.

### Determination of noise equivalent Radiation

The noise equivalent radiation (NER) is defined as the ratio of the standard deviation  $\sigma$  of the dark current to the responsivity of the instrument [Bernhard and Seckmeyer, 1999]. It depends on the integration time, usually becoming smaller with increasing integration time. For the determination of NER it is necessary to record a sufficient number of dark spectra and to calculate the standard deviation and to repeat this procedure for all integration times used in routine solar measurements. NER is used here as a generalized term valid for global irradiance, direct irradiance, actinic irradiance and radiance expressed in their respective units.

### Determination of detection threshold

The smallest signal that can be measured with a reasonable certainty is defined as  $DT(\lambda)$  in units of the measured quantity. Within this document we define:

$$DT(\lambda) = \Delta Y_{DARK}(\lambda) + \Delta Y_{STRAY}(\lambda) \quad (1)$$

where  $\Delta Y_{STRAY}$  is the uncertainty of the stray light correction. The uncertainty in the dark current correction  $\Delta Y_{DARK}$  includes the statistical noise (NER) and possible drift of the mean dark current (e.g. a drift during the time between a dark signal determination and the actual measurement). A major cause for drifts is the sensitivity of the array spectroradiometer to temperature changes.

DT is not a universal instrument feature, but depends on the solar spectrum to be measured and on the chosen instrument settings such as integration time and signal averaging during the determination of DT according to equation (1). It is important to determine DT with exactly the same instrument settings that will be used during the solar measurements.

$\Delta Y_{STRAY}$  is determined by an uncertainty analysis of the stray light correction method (see stray light section within guidelines), which is a complex task.

For array instruments the contributions to DT (equation 1 above) are not statistically independent. Furthermore the interdependencies can be nonlinear. A method on how to treat nonlinear dependencies is described in [Cordero *et al.*, 2007]. It should be noted that such methods are rather complex. Furthermore digitisation effects may contribute to the determination of DT [Häusler *et al.*, 1986]

### “Slit function” determination and wavelength registration

The complete spectral characterization of an array spectroradiometer including the determination of the wavelength corresponding to each pixel requires the determination of the slit function. In scanning spectroradiometers, this is done by scanning a well defined spectral line at small wavelength steps. The major problem with array instruments arises from the need to approximate the slit function using measurements at a limited number of wavelengths, according to the pixel density of the array. This increases the uncertainty in the determination of the shape of the slit function and the exact pixel corresponding to the wavelength of the spectral line. A nonlinear regression between the pixel numbers corresponding to different spectral lines at known wavelengths, spanning throughout the operational spectral range of the instrument, is used to assign the appropriate wavelength to each pixel of the array. Various approaches have been proposed for different types of instruments [e.g., *Chen et al.*, 2009; *Cho et al.*, 1995; *Kiedron et al.*, 2002b]. The wavelength assignment is an important procedure that should be applied to every instrument, as the wavelength scales provided usually by the manufacturers can result in deviations of several nanometres.

Remarks:

- a) For spectroradiometers situated at Earth’s surface the wavelength scale should be referred to wavelengths in air at local pressure and temperature.
- b) 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 and noise.
- c) Wavelength assignment 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 is equally applicable for all the atmospheric conditions of interest. The Fraunhofer structure in a measured spectrum 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 [*Huber et al.*, 1993; *McKenzie et al.*, 1992; *Slaper et al.*, 1995].
- d) It is recommended that a careful wavelength alignment by means of spectral lamps is performed before any correlation (e.g., those mentioned in remark c) above) method is applied.
- e) 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 [*Brueckner et al.*, 1993; *VanHoosier*, 1996], McMath/Pierce (NSF/NOAO) [*Kurucz et al.*, 1984], ETS- Gueymard [*Bernhard et al.*, 2004].
- f) Extraterrestrial spectra, which refer to vacuum wavelength (e.g., SUSIM/ATLAS3), have to be shifted to air wavelengths.

### Determination of nonlinearity

The linearity in output signal strength may be measured using a variety of methods. A comprehensive summary can be found in [*Budde*, 1983]. In the following, three main methods are briefly described, namely the ‘inverse square law’, ‘beam addition’, and ‘reference detector’ methods. Furthermore a simple linearity test is presented that takes advantage of the ability of array spectroradiometers to measure over a large range of integration times.

#### 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  $r$  from that point to the aperture. 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 nonlinearity.

Remarks:

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

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

where  $Y_{\text{read}}$  is the signal (reading) of the radiometer

$Y_{\text{read,K}}$  is the signal (reading) at the calibration level

$E$  is the irradiance corresponding to the signal  $Y_{\text{read}}$

and  $E_K$  is the irradiance corresponding to the signal  $Y_{\text{read,K}}$

- An additional complication arises from the uncertainty in determination of the reference plane of the input optics [Bernhard and Seckmeyer, 1997; Gröbner and Blumthaler, 2007].

## 2. The beam addition method

By this method, a beam from the radiation source is split into two paths, path A and path B, and it is determined whether the combined signal from both light paths (A+B) equals the sum of the signals from the individual light paths: i.e. where  $I_{(A+B)} = I_A + I_B$ . 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].

## 3. The reference detector method

This method compares the signal of the test device with the signal of a reference detector that has already been characterized for linearity. The method can be implemented by splitting the beam from a radiation source into two paths, for example by using a cubical beam splitter. One of the exit beams is directed onto the test device and the second beam on the reference detector. When changing the intensity of the radiation source (for example by adjusting its power or by using neutral density filters) the signals of the two detectors should change proportionally.

## Simple linearity test

A simple linearity test can be used to check whether the system is linear over the full dynamic range. First, measure the output of a quartz halogen lamp for a close separation so that the peak signal is close to the saturation level. Second, measure the output from the same lamp at a large separation, so the minimum signal is close to the detection threshold. In each case the dark signal offsets and the stray light must be carefully removed. Finally, take the ratio of the two measurements. The ratio as a function of wavelength should be flat. Any departures from linearity will manifest themselves as regions of non-zero slope in these ratios. The stability of linearity over several orders of magnitude can readily be achieved by these means.

## Linearity and integration time

Measurements of array spectroradiometers can usually be performed at integration times ranging between milliseconds and several seconds. By changing the integration time, the dynamical range of the system can be extended beyond the range defined by the digitization scheme. For a linear device, the net-signal should change proportionally with integration time. For example, the net-signal measured at 1000 ms should be 1000 times larger than that measured at 1 ms. Tests should be performed both with monochromatic and polychromatic (e.g., tungsten lamps) radiation sources. Since the detectability of nonlinearity is limited by the stability of the radiation sources, the characterization by a laser is limited. Experiments with several commercial spectrographs suggest that deviations from linearity are typically larger when polychromatic radiation sources are used, and these departures are usually largest at small signal levels.

It has been observed that array spectroradiometers may require a few seconds until the sensitivity stabilizes after switching the integration time.

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

Different methods apply for the determination of the spectral responsivity, according to the measured radiation quantity (irradiance, direct irradiance, actinic irradiance and radiance). It is emphasized that stray light correction is necessary for all calibration measurements as well as for solar measurements.

## Global spectral irradiance

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

Remarks:

- a) The determination of the spectral responsivity is often denoted as the irradiance calibration of a spectroradiometer.
- b) The prescribed conditions for the determination of the spectral responsivity should be stated in the lamp's certificate and must be followed closely. These include:
  - i) The distance between lamp and the reference plane of the spectroradiometer's entrance optics. This 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; Gröbner and Blumthaler, 2007].
  - ii) The alignment of the lamp and entrance optics.
  - iii) The orientation of the lamp (e.g., horizontal or vertical).
  - 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. Shunts and precision voltmeters to measure the voltage drop should be recalibrated at least every two years.
  - vi) The voltage drop across the lamp should be monitored.
- c) The accurate determination of the lamp current is crucial because variations in the lamp current of 1% result in UV radiant power of up to 10%.
- d) Since irradiance values stated in calibration certificates of standard lamps are often given in steps of 5 to 20 nm, values at intermediate wavelengths 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, including FEL calibration 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 spectral irradiance is determined by dividing the signal of the spectroradiometer when

measuring solar radiation by  $s(\lambda)$ . Appropriate corrections (e.g., for nonlinearities 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.
- h) the lamp measurement has to be corrected for stray light.

### Radiance

The spectral radiance is calibrated by measuring the radiation emitted by a calibrated reflectance plate made of optically diffuse material, which is illuminated by a calibrated lamp of spectral irradiance, placed at the distance specified by its certificate. A baffle with an opening is placed between the lamp and the plate to allow illumination only by radiation emitted directly from the lamp and to eliminate stray light from the surroundings. The radiance input optics is positioned in front of the plate e.g. at 45° angle to the diffuser plate at a distance of several centimetres, so that the field of view (FOV) is filled by radiation reflected by the plate (see Figure 2).

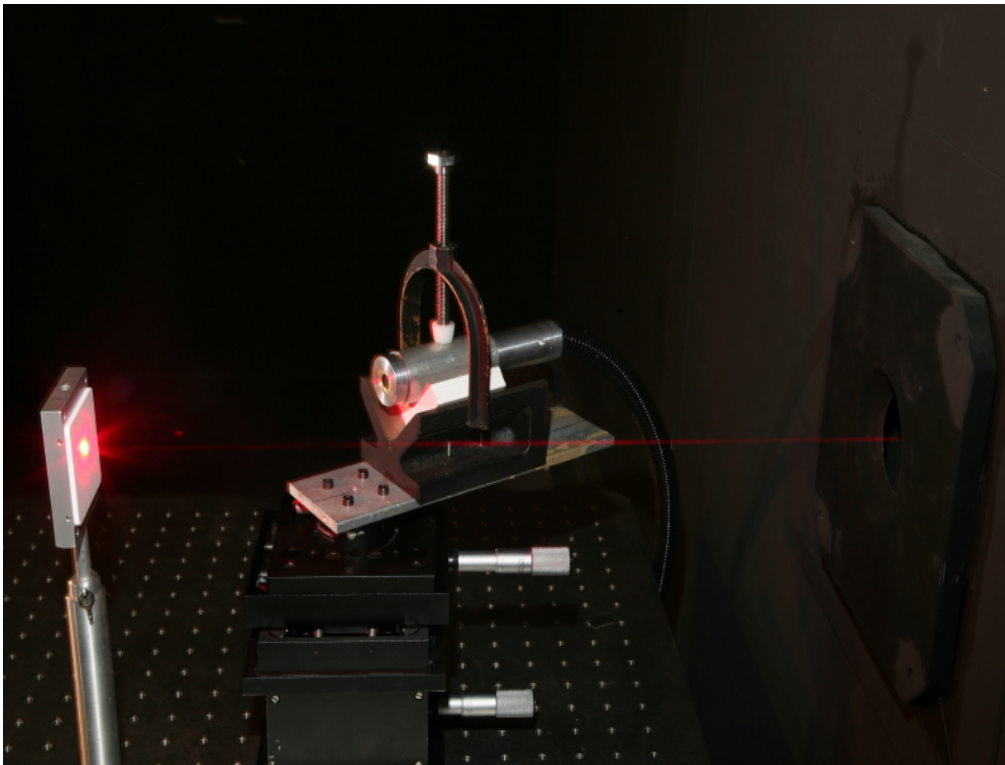


Figure 2 - Alignment of diffuser plate (left) with a HeNe Laser for a laboratory calibration of an array instrument measuring spectral radiance

If the distance is too large, the FOV may not be uniformly illuminated by the plate and the calibration procedure may be invalid. With such a setup the diffuser plate presents a uniform radiance source to the radiance optics. The radiance  $L(\lambda)$  is given by:

$$L(\lambda) = R(0^\circ / 45^\circ, \lambda) \frac{E(\lambda)}{\pi}$$

where  $R(0^\circ/45^\circ, \lambda)$  is the bidirectional reflectance factor of the diffuser plate, and  $E(\lambda)$  is the spectral irradiance of the calibrated lamp at the reference distance interpolated to the designated wavelength  $\lambda$ .

Alternatively, a calibrated integrating sphere may be used to produce a uniform radiance field  $L(\lambda)$ , which is measured by the spectroradiometer. The sphere is illuminated by a lamp of spectral irradiance mounted at its entrance port, while the radiance entrance optics of the spectroradiometer is positioned at the exit port of the sphere. More details for both methods can be found in [Pissulla et al., 2009].

The remarks for calibration of global spectral irradiance also apply.

### **Spectral direct irradiance**

In principle the spectral responsivity for direct irradiance is determined analogously to the responsivity for global irradiance: the signal of a spectroradiometer while measuring 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. It is necessary to ensure that the FOV of the direct optics does not limit the view of the lamp's bulb. For this it might be necessary to use a larger distance between lamp and entrance optics than indicated in the lamp's certificate and to correct the irradiance given in the certificate by applying the inverse square law. However, an additional uncertainty arises because the lamp is not an ideal point source. Another option to avoid the problem of limiting FOV could be to remove the limiting baffles of the input optics while measuring the lamp at the nominal distance given in the certificate, ensuring that radiation from other sources is excluded.

Finally it is sometimes possible to determine the spectral responsivity for direct irradiance with the 'Langley method' [Liou, 2001]. However, this requires cloud free and very stable conditions (e.g., aerosols and ozone) for several hours of a day, ideally including morning and afternoon. Usually these conditions occur only at high altitude stations.

The remarks for calibration of global spectral irradiance also apply.

### **Spectral actinic irradiance**

Actinic irradiance calibration is performed in a similar way as for irradiance. The correct determination of the distance between the reference plane of the input optics and the lamp is important and should be performed with great care [Hofzumahaus et al., 1999]

See also remarks described in section global spectral irradiance

### **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 signal produced by the lamp should be compared with previous 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 should also be intercompared regularly with other lamps [Webb et al., 1998]. Stability of spectroradiometers can be monitored by measuring working standard lamps mounted in specially designed enclosures which are attached in very repeatable way to the entrance optics. The operating conditions of the lamps should comply with the operational specifications discussed in the previous paragraph.

### **Stray light corrections**

Stray light is a serious problem of array spectroradiometers because it limits the detectable irradiance and if not corrected is a large contribution to the overall uncertainty.

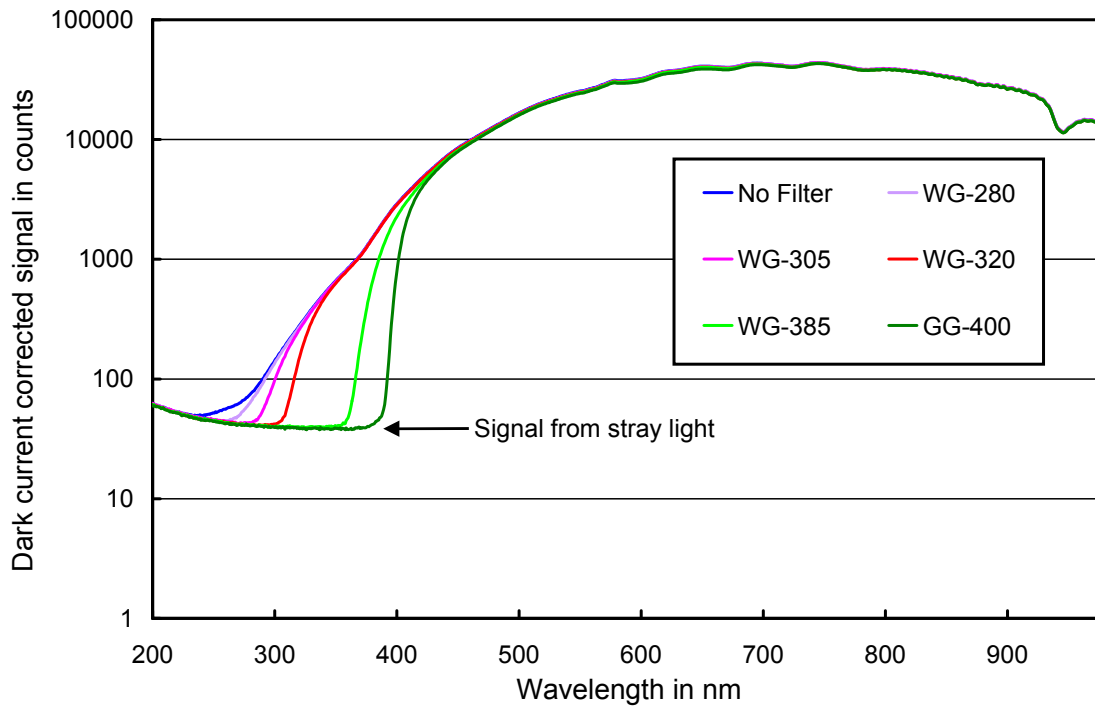


Figure 3 - An example of stray light determination from a spectrograph using cut-off filters

Figure 3 shows measurement of a FEL 1000-W tungsten-halogen lamp with an array spectroradiometer. To demonstrate the effect of stray light, several cut-off filters were placed between lamp and the radiometer's input optics. These filters block radiation below a certain wavelength. For example, the GG-400 filter attenuates radiation with wavelengths below 380 nm by more than five orders of magnitude but has a transmission of more than 90% above 420 nm. Measurements with the spectroradiometer should therefore increase by the same amount between 380 and 420 nm. The figure shows that this is not the case: signals below 380 nm are larger than 35 counts, which is only about three orders of magnitude below the maximum signal. The signal below 380 nm is stray light stemming from photons with wavelengths longer than 400 nm. The figure indicates that the stray light level does not have to be constant but may increase or decrease with decreasing wavelength. Because of this spectral dependence, which is present in all array radiometers, it is not sufficient to subtract measurements at short wavelengths (e.g. 200 nm) from the spectrum to correct for stray light.

Stray light corrections may be performed by the following methods

- 1) Using a tuneable laser or a set of spectral lines to determine the stray light in the spectral range far from the measured line [Zong *et al.*, 2006].
- 2) Using a combination of method 1 and use one cut-off filter [Kreuter and Blumthaler, 2009].
- 3) Using a deconvolution method.

#### Method 1

According to this method [Zong *et al.*, 2006], several monochromatic light sources are measured and the "stray light distribution function" (SDF) is characterized for different wavelengths. The stray light correction matrix  $C$ , based on the SDF matrix  $D$ , is derived by

$$C = [I + D]^{-1}$$

where  $I$  is the identity matrix.

The instrument's response for stray light is corrected using the equation:

$$Y_{IB} = C \cdot Y_{meas}$$

where  $Y_{meas}$  is the column vector of measured signals,

$Y_{IB}$  is a column vector of stray light corrected signals.

## Method 2

According to this method [Kreuter and Blumthaler, 2009], the spectral line spread function is measured at a single line in the blue/UV wavelength range using a laser source, and the line shape is approximated with an analytical function. The stray light distribution functions (SDF) for each wavelength is inserted in the columns of a square matrix. The inverse of the SDF plus the identity matrix is the desired stray light correction (C in the formulation of method 1). In addition one cut-off filter is used to determine the stray light of the calibration lamp and the ozone cut-off is used for solar measurements.

## Method 3

Method 3 is a deconvolution method described in [Jansson, 1984; Kiedron et al., 2002a; Kiedron et al., 2002b]

Method 1 requires that the SDF is measured over more than 5 orders of magnitude. This is difficult in practice. In addition, the stray light contribution from wavelengths above the upper sensitivity limit of the instrument cannot be determined. The major advantage of method 2 is that the stray light can in principle be determined for any source.

## 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) The stability of the spectroradiometer should be checked 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.

## Acknowledgements

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## 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 carrying out a complete 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 recognised 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].

### Actinic flux

See **Spectral Actinic irradiance**

### Actinic irradiance

Is the integral over all wavelengths of interest of the spectral actinic irradiance. It has units  $\text{Wm}^{-2}$ .

### 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

### Bandwidth

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

### 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  $f_2(\varepsilon, \varphi)$ :

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

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

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

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

The cosine error may be wavelength dependent. In this case these quantities must be considered as spectral quantities.

### Dark current

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

The detection threshold  $DT$  is the smallest radiation quantity - in this context spectral irradiance, spectral radiance or spectral actinic irradiance - that can be detected by an instrument with a reasonable certainty.

### Direct 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.

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

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].

### Erythemally weighted irradiance $E_{CIE}$

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

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

### 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  $\vartheta$  is the solar zenith angle

## Luxmeter

Instrument measuring illuminance. Illuminance may be calculated from measurements of irradiance using the following equation:

$$E = K_m \int_{380\text{nm}}^{780\text{nm}} E_G(\lambda) V(\lambda) d\lambda$$

Where  $E$  is the illuminance,  $K_m = 683 \text{ lm/W}$  is the photometric radiation equivalent illuminance,  $E_G(\lambda)$  is the spectral irradiance and  $V(\lambda)$  is the normalized relative responsivity of the human eye for daylight vision. (DIN 5032, Teil 2)

## Maximum irradiance

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

## Noise equivalent Radiation (NER)

The noise equivalent radiation (NER) is defined as the ratio of the standard deviation  $\sigma$  of the dark current to the responsivity of the instrument [Bernhard and Seckmeyer, 1999]. It depends on the integration time, usually becoming smaller with increasing integration time.

## Nonlinearity

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].

The expression  $f_3(Y)$  quantifies the correction for nonlinearity to be applied to measured irradiance

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

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

## Precision

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

- The test result is a value of the quantity to be measured by completely carrying out a specified measurement method, once.
- 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 [DIN, 1984]. 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, and 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. 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 $\Phi$**

Radiant energy  $dQ$  per time interval  $dt$ .

### **Radiance**

Is the integral over all wavelengths of interest of the spectral radiance.

### **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 [DIN, 1984]. For radiation measurements, lamps which are supplied by national standard laboratories (e.g., NIST, NPL, and PTB) are usually considered as reference standards.

### **Sampling wavelength interval**

The sampling wavelength interval is defined as the wavelength interval between subsequent measurements of a spectrum. In the context of this document the sampling interval is the deduced wavelength separation of adjacent pixels.

### **Signal-to-Noise ratio (SNR)**

Ratio between the average readings  $\bar{Y}$  of a radiometer calculated from sufficient single measurements to the standard deviation  $\sigma_Y$  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.

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

For the determination of the SNR, all measurements should be recorded in the same manner, i.e., with the same integration time 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  $\lambda_0$  [CIE, 1984; Kostkowski, 1997]. The slit function should be normalized to 1 at  $\lambda_0$ . The slit function is sometimes denoted slit-scattering function.

### **Spectral Actinic irradiance**

Spherically integrated spectral radiance at a point in the earth's atmosphere, originating from the Sun's direct beam and any scattered components. Often this quantity is called scalar irradiance or actinic flux density. It has units  $\text{Wm}^{-2}\text{nm}^{-1}$ .

$$F_{\lambda} = \int_{4\pi} L_{\lambda} d\Omega$$

### Spectral radiance $L_{\lambda}$

Spectral radiance can be a source or a receiver based quantity. In this document it is usually used as a receiver based source. Here we define it in terms of a receiver based quantity.

$L_{\lambda}$  is the radiant energy  $dQ$  per time interval  $dt$ , per wavelength interval  $d\lambda$ , per area  $dA$ , and per solid angle  $d\Omega$  on a receiver oriented normal to the source.

$$L_{\lambda} = \frac{dQ}{dt dA d\lambda d\Omega}$$

### Spectral responsivity $s(\lambda)$

Ratio of the radiometer output  $dY(\lambda)$  by the radiometer input  $dX(\lambda)$  at wavelength  $\lambda$  [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

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, direct irradiance, actinic irradiance or radiance 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. Therefore, if measurements of solar irradiance at 285 nm are above the noise level, e.g.  $1 \cdot 10^{-4}$  W/(m<sup>2</sup> nm), the amount of stray light at 285 nm in the sense of this document is greater than  $1 \cdot 10^{-4}$  W/(m<sup>2</sup> 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  $0.3 \mu\text{m} - 3 \mu\text{m}$ . In meteorology, short-wave global irradiance is usually denoted as global radiation. 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). The global average ozone amount is close to 300 DU, which corresponds to a layer of thickness 3 mm at STP.

#### 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/cm<sup>2</sup>.

### **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 [DIN, 1984]. 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; 1998], the UV index is calculated considering the following items:

1. Calculation of the erythemally weighted irradiance  $E_{\text{CIE}}$  (see above) by utilisation of the CIE action spectrum [McKinlay and Diffey, 1987] normalized to 1.0 at 298 nm.
2. A minimum requirement is to report the daily maximum UV index [WMO, 1998].
3. The index is expressed by multiplying the weighted irradiance in  $\text{Wm}^{-2}$  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.

### **UV-A radiation**

Electromagnetic radiation between 315 and 400 nm [CIE, 1970].

### **UV-B 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 assignment**

Assignment of a wavelengths scale to the pixels of a spectroradiometer. This is sometimes also called wavelength calibration. The agreed wavelength scale may be represented by spectral lines of a low-pressure mercury lamp.

**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 [DIN, 1984].

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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