Designation: G130 – 12

Standard Test Method for Calibration of Narrow- and Broad-Band Ultraviolet Radiometers Using a Spectroradiometer[1]

This standard is issued under the fixed designation G130; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Accurate and precise measurements of ultraviolet irradiance are required in the determination of the radiant exposure of both total and selected narrow bands of ultraviolet radiation for the determination of exposure levels in (*1*) outdoor weathering of materials, (*2*) indoor accelerated exposure testing of materials using manufactured light sources, and (*3*) UV-A and UV-B ultraviolet radiation in terms both of the assessment of climatic parameters and the changes that may be taking place in the solar ultraviolet radiation reaching earth.

Although meteorological measurements usually require calibration of pyranometers and radiometers oriented with axis vertical, applications associated with materials testing require an assessment of the calibration accuracy at orientations with the axis horizontal (usually associated with testing in indoor exposure cabinets) or with the axis at angles typically up to 45° or greater from the horizontal (for outdoor exposure testing). These calibrations also require that deviations from the cosine law, tilt effects, and temperature sensitivity be either known and documented for the instrument model or determined on individual instruments.

This test method requires calibrations traceable to primary reference standards maintained by a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance.

1. Scope

1.1 This test method covers the calibration of ultraviolet light-measuring radiometers possessing either narrow- or broad-band spectral response distributions using either a scanning or a linear-diode-array spectroradiometer as the primary reference instrument. For transfer of calibration from radiometers calibrated by this test method to other instruments, Test Method E824 should be used.

NOTE 1—Special precautions must be taken when a diode-array spectroradiometer is employed in the calibration of filter radiometers having spectral response distributions below 320-nm wavelength. Such precautions are described in detail in subsequent sections of this test method.

1.2 This test method is limited to calibrations of radiometers against light sources that the radiometers will be used to measure during field use.

NOTE 2—For example, an ultraviolet radiometer calibrated against natural sunlight cannot be employed to measure the total ultraviolet irradiance of a fluorescent ultraviolet lamp.

1.3 Calibrations performed using this test method may be against natural sunlight, Xenon-arc burners, metal halide burners, tungsten and tungsten-halogen lamps, fluorescent lamps, etc.

1.4 Radiometers that may be calibrated by this test method include narrow-, broad-, and wide-band ultraviolet radiometers, and narrow-, broad, and wide-band visible-region-only radiometers, or radiometers having wavelength response distributions that fall into both the ultraviolet and visible regions.

NOTE 3—For purposes of this test method, narrow-band radiometers are those with $\Delta\lambda \leq 20$ nm, broad-band radiometers are those with 20 nm $\leq \Delta\lambda \leq 70$ nm, and wide-band radiometers are those with $\Delta\lambda \geq 70$ nm.

NOTE 4—For purposes of this test method, the ultraviolet region is defined as the region from 285 to 400-nm wavelength, and the visible region is defined as the region from 400 to 750-nm wavelength. The ultraviolet region is further defined as being either UV-A with radiation of wavelengths from 315 to 400 nm, or UV-B with radiation from 285 to 315-nm wavelength.

[1] This test method is under the jurisdiction of ASTM Committee G03 on Weathering and Durabilityand is the direct responsibility of Subcommittee G03.09 on Radiometry.

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1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E772 Terminology of Solar Energy Conversion

E824 Test Method for Transfer of Calibration From Reference to Field Radiometers

E973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell

G138 Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance

2.2 *Other Documents: CIE Publication No. 63 The Spectrodiometric Measurement of Light Sources*

3. Terminology

3.1 *Definitions:*

3.1.1 *broad-band radiometer—*radiometerric detectors with interference filters or cut-on/cut-off filter pairs having a FWHM between 20 and 70 nm and with tolerances in center (peak) wavelength and FWHM no greater than ±2 nm.

3.1.2 *diode array detector—*a detector with from a number of silicon photodiodes affixed side-by-side in a linear array and mounted in the focal plane of the exit slit of a monochromator.

3.1.3 *full width at half maximum (FWHM)—*in a bandpass filter, the interval between wavelengths at which transmittance is 50 % of the peak, frequently referred to as bandwidth.

3.1.4 *narrow-band radiometer—*a relative term generally applied to radiometers with interference filters with FWHM ≤20 nm and with tolerances in center (peak) wavelength and FWHM no greater than± 2 nm.

3.1.5 *National Metrological Institution (NMI)—*A nation's internationally recognized standardization laboratory.

3.1.5.1 *Discussion—*The International Bureau of Weights and Measurements (abbreviation BIPM from the French terms) establishes the recognition through Mutual Recognition Agreements. See http://www.bipm.org/en/cipm-mra. The NMI for the United States of America is the National Institute for Standards and Technology (NIST).

3.1.6 *scanning monochromator—*an instrument for isolating narrow bands of wavelength of light that admits broadband light through an entrance slit, directs the light to a dispersive element (prism or grating), and uses either a single, or several interchangeable, detector(s) mounted at an exit slit. The detector is presented with dispersed light by sweeping the spectrum across the slit to illuminate the detector with a succession of different very narrow wavelength light distributions. The detector may be either a photomultiplier tube (PMT) or silicon photodiode (visible), or an ultraviolet-enhanced PMT or silicon photodiode (ultraviolet and visible), or a lead sulfide cell or other solid state detector (near infrared), etc. The dispersed spectrum is swept across the exit slit using a mechanical stage that rotates the element, usually under the control of an external microprocessor or computer.

3.1.7 *spectroradiometer—*a radiometer consisting of a monochromator with special acceptance optics mounted to the entrance aperture and a detector mounted to the exit aperture, usually provided with electronic or computer encoding of wavelength and radiometric intensity. The monochromator of such instruments is either of the linear diode (often called *diode array*) or the scanning type.

3.1.8 *wide-band radiometer—*a relative term generally applied to radiometers with combinations of cut-off and cut-on filters with FWHM greater than 70 nm.

3.2 For other terms relating to this test method, see Terminology E772.

4. Significance and Use

4.1 This test method represents the preferable means for calibrating both narrow-band and broad-band ultraviolet radiometers. Calibration of narrow- and broad-band ultraviolet radiometers involving direct measurement of a standard source of spectral irradiance is an alternative method for calibrating ultraviolet radiometers. This approach is valid only if corrections for the spectral response of the instrument and the spectral mismatch between the calibration spectral distribution and the target spectral distribution can be computed. See Test Method E973 for a description of the spectral mismatch calculation.

4.2 The accuracy of this calibration technique is dependent on the condition of the light source (for example, cloudy skies, polluted skies, aged lamps, defective luminaires, etc.), and on source alignment, source to receptor distance, and source power regulation.

NOTE 5—It is conceivable that a radiometer might be calibrated against a light source that represents an arbitrarily chosen degree of aging for its class in order to present to both the test and reference radiometers a spectrum that is most typical for the type.

4.3 Spectroradiometric measurements performed using either an integrating sphere or a cosine receptor (such as a shaped PTFE[3], or Al_2O_3 diffuser plate) provide a measurement of hemispherical spectral irradiance in the plane of the sphere's entrance port. As such, the aspect of the receptor plane relative to the reference light source must be defined (azimuth and tilt from the horizontal for solar measurements, normal incidence with respect to the beam component of sunlight, or normal incidence and the geometrical aspect with respect to an artificial light source, or array). It is important that the geometrical aspect between the plane of the spectroradiometer's source optics and that of the radiometer being calibrated be as nearly identical as possible.

NOTE 6—When measuring the hemispherical spectral energy distribution of an array of light sources (for lamps), normal incidence is defined

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Polytetrafluoroethylene

by the condition obtained when the plane of the receiver aperture is parallel to the plane of the lamp, or burner, emitting area.

4.4 Calibration measurements performed using a spectroradiometer equipped with a pyrheliometer-comparison tube (a sky-occluding tube), regardless of whether affixed directly to the monochromator's entrance slit, to the end of a fiber optic bundle, or to the aperture of an integrating sphere, shall not be performed unless the radiometer being calibrated is configured as a pyrheliometer (possesses a view-limiting device having the approximate optical constants of the spectroradiometer's pyrheliometer-comparison tube).

4.5 Spectroradiometric measurements performed using source optics other than the integrating sphere or the "standard" pyrheliometer comparison tube, shall be agreed upon in advance between all involved parties.

4.6 Calibration measurements that meet the requirements of this test method are traceable to a national metrological laboratory that has participated in intercomparisons of standards of spectral irradiance, largely through the traceability of the standard lamps and associated power supplies employed to calibrate the spectroradiometer according to G138, the manufacturer's specified procedures, or CIE Publication 63.

4.7 The accuracy of calibration measurements performed employing a spectroradiometer is dependent on, among other requirements, the degree to which the temperature of the mechanical components of the monochromator are maintained during field measurements in relation to those that prevailed during calibration of the spectroradiometer. [1]

5. Apparatus

5.1 *Reference Spectroradiometers:*

5.1.1 The spectroradiometer employed as the reference radiometer shall, regardless of whether it consists of a scanning or a linear-diode-array monochromator, be calibrated in accordance with the procedures specified by G138. CIE Publication 63, or specific calibration procedures required by the manufacturer.[4] and the manufacturer.

5.1.1.1 It is recommended that the reference spectroradiometer, or one of its exact type, has been a participating spectroradiometer in an intercomparison of spectroradiometers either managed, sponsored, or sanctioned by a national metrological laboratory, or another appropriate body. Such interlaboratory comparisons should include the spectral range of interest in the application. See references [2-6]

5.1.1.2 Alternatively, it is recommended that the reference spectroradiometer shall be calibrated by measurement of a primary spectral irradiance standard reference lamp source produced by a national metrological laboratory,(NMI) or measurement of a transfer standard lamp generated by comparison with a primary standard of spectral irradiance lamp..The traceability of the lamp calibration source and attendant uncertainty shall be reported.

5.1.2 If a linear diode-array spectroradiometer is used as the reference, it shall possess focusing optics internal to the monochromator and a linear diode array detector with a sufficient number of diodes that, together, result in a resolving power of 1 nm or less. The monochromator's dispersive element shall be a holographic grating, and the spectroradiometer's acceptance optics shall consist of either an integrating sphere with appropriately sized and oriented light entrance port, or a shaped translucent diffuser plate whose deviation from true cosine response is small and known. A further requirement is that the stray light rejection be determined for any diode-array spectroradiometers used to perform this test method and that it be 10^5 or greater in the spectral region for which calibration is required.

5.1.2.1 A diode-array spectroradiometer shall not be used as the reference instrument for ultraviolet wavelengths shorter than 300-nm wavelength. Further, when used in the wavelength region between 300 and 320-nm wavelength, evidence shall be presented with the calibration reports, or certificates, showing that the stray light has been eliminated by a combination of internal baffling, merging of two determinations in which the wavelength region below 320-nm is measured employing secondary filters to reject all wavelengths longer than 320 nm, other techniques, or combinations of these.

5.1.3 When an integrating sphere is used, the exit port (to the monochromator) and entrance port (that represents the receiver) should be oriented 90° to each other and the sphere should be equipped with a baffle to occlude all light that might reach the exit directly from the entrance port.

5.1.4 When a pyrheliometer-comparison tube, or other view-limiting device, is used for the purpose of calibrating, for example, ultraviolet pyrheliometers, the pyrheliometer-comparison tube should ideally be affixed to the entrance port of the integrating sphere such that the sphere's entrance port becomes the aperture stop of the view-limiting device. Under most circumstances, the pyrheliometer comparison tube should possess the optical geometry defined by the World Meterorological Organization, the principal one being a 5.6° field of view.

NOTE 7—When the sphere's entrance port is the occluder's aperture stop, no calibration of the spectroradiometer is required independent of the calibration with only the integrating sphere in place. If the occluder's aperture stop is integral with the occluder and of different smaller dimension than the sphere's entrance port, the spectroradiometer must be calibrated with the occluder attached to the integrating sphere ... resulting in greater uncertainties and the possibilities of significant errors.

5.2 *Computational Facilities*—The computer-based computational facilities used to import the raw data with respect to wavelength and intensity should be capable of providing analyzed spectral irradiance information integrated across any wavelength band chosen.

5.3 *Instrument Mounts:*

5.3.1 *Equatorial Mount*—An altazimuthal or equatorial, follow-the sun mount that is equipped with a platform on which the spectroradiometer is mounted is required for all hemispherical normal-incident and direct (beam) calibrations measurements.

[4] The *Spectrodiometric Measurement of Light Sources*, Publication No. 63, The International Commission on Illumination (CIE).

5.3.2 *Tilt Table*—A stable, adjustable tilt table having tilt and azimuth adjustments is required for global solar radiation measurements (for example, at horizontal orientation) and hemispherical measurements at specified azimuthal and tilt positions.

NOTE 8—An altazimuthal mount so equipped also may be used as the tilt table.

5.3.3 *Optical Platform*—A stable, platform equipped with height adjustment is required for use in measuring the calibrating radiometers against light sources such as arrays, solar simulators, special lamps, and burners, etc.

NOTE 9—When using a fiber-optic/integrating sphere source configuration to calibrate radiometers, for example, against Xenon-arc lamps, carbon arcs, and other burners employed in indoor exposure cabinets, special fixtures may be required to rigidly mount and present the source optics to the source of irradiance. For UV-A and UV-B calibrations, the fiber-optic bundle must be constructed of quartz fibers.

6. Procedure

6.1 Calibrate the spectroradiometer in accordance with G138, the manufacturer's instructions, or CIE Publication 63[4] unless the spectroradiometer's calibration is known to be stable within 30 days of the last intensity and wavelength calibration required.

6.1.1 Verify calibration with a spectral irradiance measurement over the spectral response region of the test instrument, of the calibration source as an unknown. Alternatively, a 'check source', measured at the time of the latest calibration, using the newest calibration response of the spectroradiometer at that time, can be remeasured. Measured spectral irradiance differences between the spectral irradiance of the check lamp at the latest calibration and at the time of the test unit calibration which exceed the smaller of +/-5% and the expected measurement uncertainty of the system indicate recalibration is required. See references [2-4]

6.2 Select the wavelength step interval for the spectral measurement

6.2.1 For weathering and exposure-testing applications requiring the measurement of UV-B radiation employing a single-filter radiometer, select a wavelength step interval of 1 nm regardless of the FWHM and central wavelength of the filter radiometer being calibrated.

6.2.2 For weathering and exposure-testing applications requiring the measurement of UV-B and UV-A radiation using a multiple-filter radiometer, select a wavelength step interval which is the smaller of 5% of the FWHM of each of the specific filters of the radiometer or 1 nm.

6.2.3 For all other applications, such as UV-A, total ultraviolet, and specific narrow-band radiometry, select a wavelength step interval which is the smaller of 5% of the FWHM of the instrument's spectral response function, or 1 nm, unless another interval is agreed upon between the parties involved.

NOTE 10—When an application either requires, permits, or will likely result in, the use of filter radiometers from different manufacturers, calibration to the FWHM of the instrument's spectral response functions will result in significant instrument-to-instrument differences when measuring sources having the same spectral energy distributions. In this case, the users or specifications should state the exact wavelength interval that will be used for all calibrations.

6.3 *Measurement of Light-Source Radiation for Calibration Using Sunlight:*

6.3.1 Mount the radiometer to be calibrated in the geometrical configuration and aspect that will be employed in its end-use application.

6.3.2 Affix the spectroradiometer to the mount required for the measurements being performed (for example, an equatorial, follow-the-sun mount; a tilt table; or, a horizontal bench).

6.3.3 Ensure that both the radiometer being calibrated and the spectroradiometer are positioned at the same azimuth angle with respect to the sun, and at the same tilt from the horizontal.

6.3.4 Perform these calibration measurements only under clear sky conditions by ensuring that no cloud is within less than 30° of the sun during any one measurement sequence.

6.3.5 Determine the spectral irradiance distribution of the sun in conformance with the procedures specified in CIE Publication 63.[4] or the spectral measurement procedures supplied by the manufacturer of the reference spectroradiometer. Perform not less than five spectral irradiance measurements separated by at least 30 min. Ensure that at least one measurement is taken at, or not greater than 30 min from solar noon.

6.3.6 During the period of the spectral irradiance measurements, record the instantaneous voltage signals of the radiometer, or radiometers, being calibrated to obtain at least 5 readings at a frequency not less than every minute during the period of the spectral irradiance measurements.

6.4 *Calibration Using Manufactured Light Sources:*

6.4.1 Mount the radiometer to be calibrated in the geometrical configuration and aspect that will be employed in its end-use application. Ensure that the receptor aperture (for example, entrance port) of the spectroradiometer's sphere is at the same distance with a tolerance of +/- 1 mm from ta reference point on the source as the radiometer being calibrated, and ensure that the reference spectroradiometer and radiometer being calibrated have the same field of view of the source lamp in terms of solid angle of the lamp's subtended.

6.4.2 Determine the geometrical aspect between the radiometer's aperture and the source by measuring the angle subtended between the aperture and the source. For non-circular lamp envelops, measure the angle in two orthogonal planes, one of which is coincident with the long axis of the lamp.

6.4.3 Record the voltage signals of the radiometer being calibrated so as to obtain at least 5 measurements over the equivalent to the period of the spectral measurement to establish the stability of the reference light source output . The percentage variation in the range of readings [(maximum minus minimum)/(maximum + minimum) x 100] should be reported as the stability of the source. Stability of better than 1.0% is required.

6.4.4 Carefully position the spectroradiometer and the source optics so that the aperture of the cosine receptor, or the integrating sphere (depending on the type of spectroradiometer being used), possesses the same geometrical aspect as the test radiometer being calibrated, and is the same distance (within +/1 mm) from a reference point on the source. Ensure that the axis of the spectroradiometer's integrating sphere, or cosine receptor passes through both the entrance port and the center of the lamp. When measuring a single fluorescent tube lamp, or a Xenon-arc lamp, align the source optics with the center of the lamp and measure distance from the sphere aperture to the the reference point on the source..

6.4.5 Determine the spectral irradiance distribution of the light source being employed in conformance with the procedures specified in CIE Publication 63[4] or the spectral measurement procedures supplied by the manufacturer of the reference Spectroradiometer. Take not less than three spectral irradiance measurements spread over a 20-min period.

6.5 *Computation of Instrument Sensitivity Constants When Calibrated to Sunlight:*

6.5.1 Calculate the approximation to the integral of the spectral irradiance data obtained by the spectroradiometer (see section 5.2.4) in the wavelength band corresponding to the wavelength band of, or assigned to, the radiometer being calibrated. For the most accurate calibration, the integral should be over the full bandwidth (passband limits) of the test radiometer:

$$E_s(j) = \int_{\lambda_1}^{\lambda_2} E_{x,\lambda}(ij)\, d\lambda \quad (1)$$

where: $E_s(j)$ is the integrated irradiance for the spectral measurement $j = 1$ *to* 3 λ_1 and λ_2 are the passband wavelength limits of the radiometer and $E_s,\lambda(ij)$ is the jth spectral irradiance scan. The means for calculating the approximation of the integral from disctrete digital data shall be reported.

NOTE 11—Examples of integration techniques are the trapezoid rule, Simpson rule, or 'calculated using the spectroradiometer manufacturer supplied software'.

NOTE 12—The wavelength bands to which a radiometer is calibrated may be slightly larger, or slightly smaller than the "advertised" band-pass for the radiometer. The essential requirement is that the out-of-band spectrum of the reference light source, and, hence, the field source, must not represent a significantly greater irradiance than the average in-band irradiance, and the out-of-band irradiance must not exhibit poorer temporal stability than the average in-band irradiance.

6.5.2 For each Jth value of integrated spectral irradiance $E_s(j)$ measured with the test radiometer in scanning the interval j corresponding to the time interval of the reference spectral measurement:

$$V_r(j) = \frac{\sum_{i=1}^{n} V_r(ij)}{n(j)} \quad (2)$$

where: $V_r(ij)$ is the voltage reading i recorded by the radiometer being calibrated in the measurement series j summed from the first measurement $i = 1$ to the *nth* measurement, and where $n(j)$ is the number of readings taken during the measurement series.

6.5.3 Compute the j test radiometer calibration responsivities $R(j)$ or calibration factors $F(j)$ or each measurement of the j spectral irradiance measurements of the reference light source by:

$$R(j) = \frac{V_r(j)}{E_s(j)} \quad (3)$$

Or

$$F(j) = \frac{E_s(j)}{V_r(j)} \quad (4)$$

When the instrument employed to measure the spectral irradiance in the wavelength interval of interest is a linear diode array spectroradiometer, nearly simultaneous measurements of spectral irradiance may, and should, be made within 2 seconds of the test radiometer voltage or signals. Equations 3 and 4 above may be applied to each pair of (integrated) spectral and test instrument signal measurements

6.5.4 The final calibration responsivity R or calibration factor F is then computed from the mean of all $R(j)$ and $F(j)$'s using the following equations:

$$R = \frac{\sum_{j=1}^{m} R(j)}{m} \quad (5)$$

$$F = \frac{\sum_{j=1}^{m} F(j)}{m} \quad (6)$$

Where m is the number of pairs of spectral irradiance integrals and test radiometer average readings.

6.5.5 For each of the average value calculations of $Vr(j)$, $R(j)$ and $F(j)$, (eq. 2,5,6) the standard deviation of each series shall be computed and reported. These values will contribute to the uncertainty estimate for the resulting responsivities or calibration factors.

7. Report

7.1 Report the following information:

7.1.1 *Title*—The title shall describe the radiometer calibrated and the reference light source that was used. For calibrations performed against the sun, only the most pertinent information should be included in the title (for example, normal incidence or tilt),

7.1.2 Manufacturer, model, serial number, and manufacturer's designated wavelength band-pass or radiometer(s) calibrated,

7.1.3 The wavelength step interval, or intervals, for which the calibration was determined and for which the calibration is valid,

7.1.4 Manufacturer, model, serial number, and source optics of spectroradiometer used. Report most recent calibration date, estimated spectral measurement uncertainty, and traceability,

7.1.5 *Light Source Description*—If the sun, describe all pertinent information (solar time, aspect, component). If a lamp, include manufacturer, model number, serial number (if available), distance and aspect, and voltage (if other than standard line voltage). If a standard lamp is used as the reference source, report manufacturer, model number, serial number, calibration reference, traceability, and amperage used,

7.1.6 Radiometer(s) calibration responsivity R or calibration instrument constant F derived in 6.5.4,

7.1.7 Date of calibration,

7.1.8 Apply a calibration label or decal to the radiometer showing as a minimum the instrument responsivity R, or calibration factor F, the estimated uncertainty in the responsivity or factor, and the date of calibration.

8. Precision and Bias

8.1 Precision and bias for the reference spectroradiometer calibration are the result of the quality of the Spectroradiometer instrumentation, and the traceability of the reference lamp used to calibrate the Spectroradiometer. Typical total uncertainty in primary standards of spectral irradiance in the spectral region from 250 nm to 400 nm is on the order of 1.35%5 [1,3-6]. These values are based on international comparisons of spectral irradiance reference scales. Such comparisons are analysed in accordance with the *Guidelines for CCPR Comparisons Report Preparation* [2], and a re-evaluation of the results taking into account the instability of some of the transfer lamps. Excluding a few wavelengths,all participants agree with each other within ±1.5% to ±2.0%, depending on wavelength, and spectral irradiance scale development techniques.

8.2 The bias and precision of transfers from primary standards of spectral irradiance to working standards includes not only the primary standard uncertainty, but bias and precision of the transfer process [3-6]. This can only be developed by analysis of repeated transfers and the performance of power supplies, current monitoring equipment, fixtures, and set-up geometry for the spectroradiometers used in the transfer. Typically each transfer results in at least a factor of 2.5 to 3 inflation in the uncertainty in the spectral distribution of the working standard. [6-9]

8.3 Precision of the calibration process may be estimated based on the standard deviation of the averages calculated in equations 2, 5 and 6. Typical standard deviations are on the order of 1% of the resultant means.[3-10]

8.4 Bias estimates can be estimated from applying the calibration factor or responsivity of the test instrument to obtain irradiance values that could be compared with integrated spectral irradiance measurements under various conditions. Typical bias values on the order of 3% to 5% have been observed, [4-6,10] due to 1) changing spectral irradiance distributions, 2) radiometer characteristic such as cosine response, temperature response, etc. 3) high signal to noise ratio issues, particularly at low irradiance levels and in the UV-B band of natural sunlight where the signal is small.

8.5 The combination of reference standard uncertainty (1.3%), standard deviation of calibration factors (1.0%), calibration source stability (1.0%) and instrument characteristics (for both the reference spectroradiometer and the test radiometers— 3% to 5%) will result in total uncertainties on the order of 3% to 8%, depending on calibration conditions, sources, and references.[9,10]

8.6 The precision in determining the instrument constant of an ultraviolet field radiometer used to measure the sun is influenced by sky conditions, and particularly by variations in cosine response when performing calibrations at low solar elevations and in the stability of the sun's ultraviolet spectrum during the calibration sequence. [3-6,10]

8.7 The precision in determining the instrument constant of ultraviolet radiometers designed to measure the radiant exposure of manufactured ultraviolet sources is influenced in large part on the temporal stability of the source during the calibration sequence. [3-6]

8.8 Reproducibility between instruments of the same manufacturer will depend on differences in the spectrum under which they were calibrated. [9,10] Likewise, agreement between instruments of different manufacture will depend on differences in their spectral response distribution functions, as well as on the source spectrum against which they were calibrated [6-10].

8.9 Numerical differences and the standard deviation for data sets must be cannot be estimated. Hence, a need exists for conducting either field intercomparisons or interlaboratory measurements of reference sources (other than the standard lamps against which the reference spectroradiometers are calibrated). [3-6,10] See Annex A for mandatory information related to the magnitudes and sources of bias, precision,and uncertainty extracted from selected references.

ANNEX

A1. Examples of Bias, Precision, and Uncertainty in Ultraviolet Spectral and Broadband Instrument Intercoparisons

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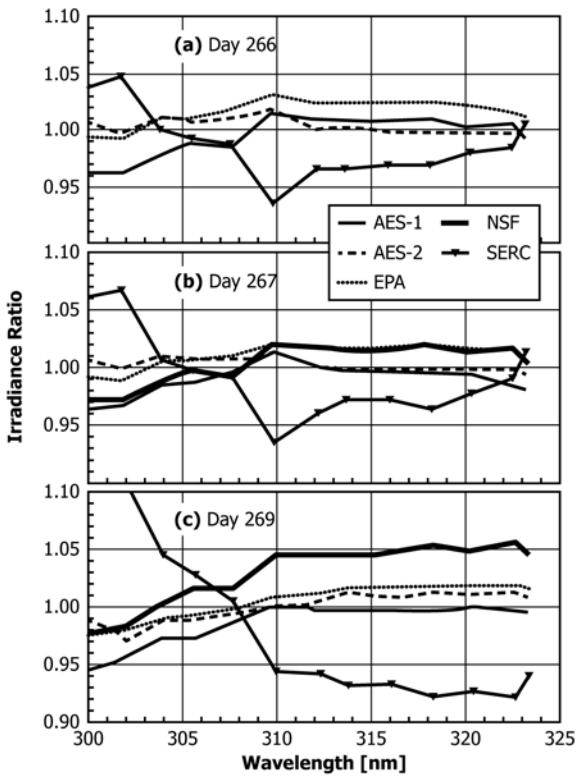

Fig. 6.11. Ratio of solar irradiance measured by each instrument to the average irradiance as a function of wavelength by all the instrumentson the days indicated inthe panels at 19:00 h. The solar irradiances determined by the scanning instruments were convolved with the transmittances of the filters of the SERC instrument.

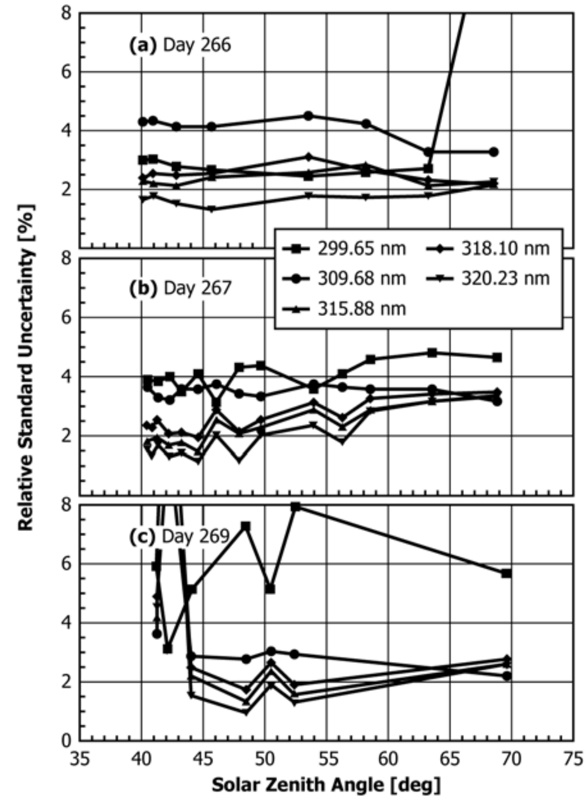

Fig. 6.12. Relative standard uncertainty of the solar irradiances as a function of solar zenith angle at the wavelengths indicated in the legend determined by all the instruments on the days indicated in the panels. The solar irradiances determined by the scanning instruments were convolved with the transmittances of the filters of the SERC instrument.

FIG. 1 Ratios of test spectroradiometer solar spectral distributions in the ultraviolet with respect to the average reference spectral distribution derived from three reference spectrometers. The results reflect measurements during outdoor intercomparisons. All spectrometers were calibrated using a common spectral irradiance standard lamp immeadiately before, during and after the comparison measurements. Similar results are described in references 3,4, and 5.

H. Diémoz et al.: First intercomparison of UV radiometers in Italy

Table 4. Total uncertainty (%) of the spectroradiometer. The total radiometer uncertainty is calculated as the squared sum of contributions.

Contribution	300 nm 50°	300 nm 75°	310–400 nm 50°	310–400 nm 75°
Radiometric uncertainty	2.7	2.7	2.7	2.7
Diffuser temperature	0.6	0.6	0.6	0.6
Angular response	0.4	0.4	0.8	0.8
Non-linearity	0.5	0.5	0.5	0.5
Instability	0.4	0.4	0.4	0.4
Statistic noise	0.8	4.6	0.3	0.9
Wavelength misalignment	2.1	2.4	0.9	0.9
Total (K = 1)	3.6	5.9	3.0	3.2
Expanded (K = 2)	7.2	12	6.0	6.4

FIG. 2 Table 4 From Reference [10], the table displays uncertainty components and contributions to spectroradiometers compared outdoors as described in the reference. Note the variation of uncertainty as a function of zenith angle.

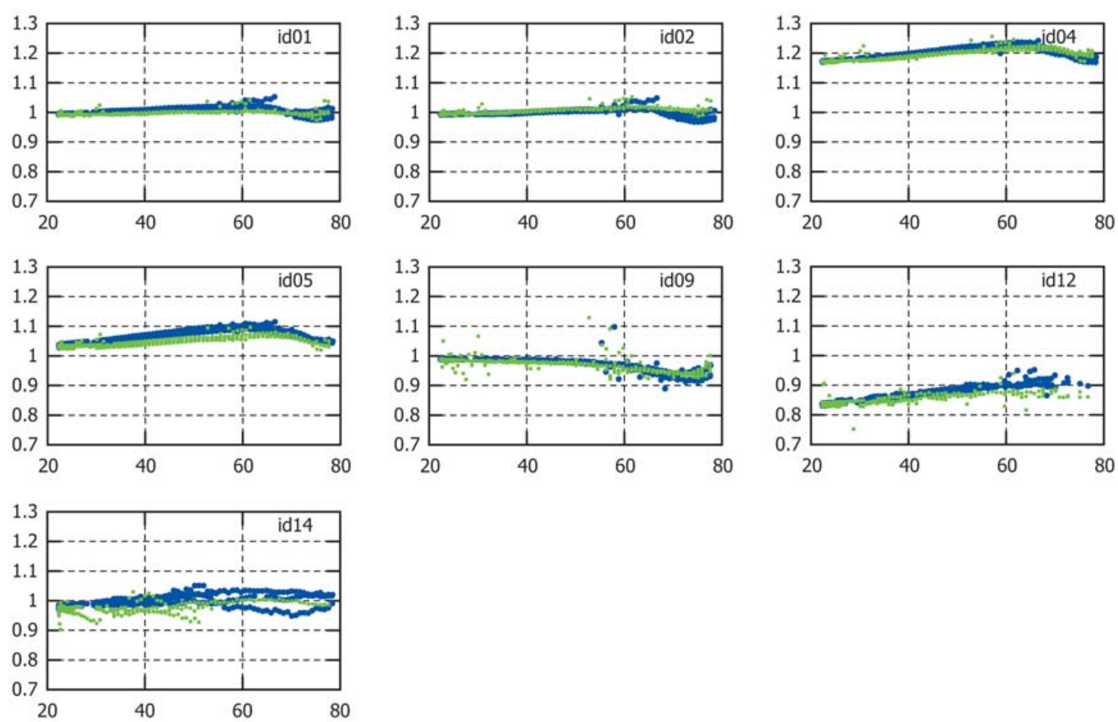

Fig. 8. Ratios between clear-sky UV-A irradiance measurements with user instruments and the reference (vertical axis) against the zenith angle (horizontal axis). Morning (blue) and afternoon (green) measurements are plotted separately.

www.atmos-meas-tech.net/4/1689/2011/ Atmos. Meas. Tech., 4, 1689–1703,

FIG. 3 Figure from reference [10] showing the zenith angle (combined geometric and spectral response sensitivity) dependence of the ratio of UV-A broadband radiometers calibrated with respect to a reference spectroradiometer. Most radiometers are within about 10% of the reference,but deviations up to 20% are observed for a few radiometers

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