Designation: G207 – 11

Standard Test Method for Indoor Transfer of Calibration from Reference to Field Pyranometers[1]

This standard is issued under the fixed designation G207; 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 total solar and solar ultraviolet irradiance are required in: (1) the determination of the energy incident on surfaces and specimens during exposure outdoors to various climatic factors that characterize a test site, (2) the determination of solar irradiance and radiant exposure to ascertain the energy available to solar collection devices such as flat-plate collectors, and (3) the assessment of the irradiance and radiant exposure in various wavelength bands for meteorological, climatic and earth energy-budget purposes. The solar components of principal interest include total solar radiant exposure (all wavelengths) and various ultraviolet components of natural sunlight that may be of interest, including both total and narrow-band ultraviolet radiant exposure.

This test method for indoor transfer of calibration from reference to field instruments is only applicable to pyranometers and radiometers whose field angles closely approach 180° ... instruments which therefore may be said to measure hemispherical radiation, or all radiation incident on a flat surface. Hemispherical radiation includes both the direct and sky (diffuse) geometrical components of sunlight, while global solar irradiance refers only to hemispherical irradiance on a horizontal surface such that the field of view includes the entire hemispherical sky dome.

For the purposes of this test method, the terms pyranometer and radiometer are used interchangeably.

1. Scope

1.1 The method described in this standard applies to the indoor transfer of calibration from reference to field radiometers to be used for measuring and monitoring outdoor radiant exposure levels.

1.2 This test method is applicable to field radiometers regardless of the radiation receptor employed, but is limited to radiometers having approximately 180° (2π Steradian), field angles.

1.3 The calibration covered by this test method employs the use of artificial light sources (lamps).

1.4 Calibrations of field radiometers are performed with sensors horizontal (at 0° tilt from the horizontal to the earth). The essential requirement is that the reference radiometer shall have been calibrated at horizontal tilt as employed in the transfer of calibration.

1.5 The primary reference instrument shall not be used as a field instrument and its exposure to sunlight shall be limited to outdoor calibration or intercomparisons.

NOTE 1—At a laboratory where calibrations are performed regularly it is advisable to maintain a group of two or three reference radiometers that are included in every calibration. These serve as controls to detect any instability or irregularity in the standard reference instrument.

1.6 Reference standard instruments shall be stored in a manner as to not degrade their calibration.

1.7 The method of calibration specified for total solar pyranometers shall be traceable to the World Radiometric Reference (WRR) through the calibration methods of the reference standard instruments (Method G167 and Test Method E816), and the method of calibration specified for narrow- and broad-band ultraviolet radiometers shall be traceable to the National Institute of Standards and Technology (NIST), or other internationally recognized national standards laboratories (Standard G138).

1.8 *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.*

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

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2. Referenced Documents

2.1 *ASTM Standards:*[2]

E772 Terminology of Solar Energy Conversion

E816 Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers

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

G113 Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials

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

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

2.2 *Other Standards:*[3]

ISO 9847 Solar Energy Calibration of Field Pyranometers by Comparison to a Reference Pyranometer

3. Terminology

3.1 *Definitions:*

3.1.1 See Terminology E772 and G113 for terminology relating to this test method.

4. Summary of Test Method

4.1 Mount the reference pyranometer, and the field (or test) radiometers, or pyranometers, on a common calibration table for horizontal calibration. Adjust the height of the radiation receptor of all instruments to a common elevation.

4.2 Connect the signal cables from the reference and test sensors to a data acquisition system.

4.3 Adjust the data acquisition system to record data at the selected data collection interval.

NOTE 2—Data collection interval should be function of the time constant of the sensor. Sensor time constant is the period of time required for a sensor to reach 1 – 1/e = 63% of the maximum minus the minimum amplitude of a step change in input stimulus. (e is base of natural logarithms, 2.718282...). Often, "one over e" (1/e) time constants are reported for radiation sensors, for example "1/e response time = 3 seconds". This represents the time for the sensor signal to reach 37% of the full range step change representing the step change in the stimulus. Four times the 1/e time constant can be considered the time for the sensor to fully respond to a step change in stimulus.

4.4 Energize the source to be used for the transfer of calibration.

NOTE 3—It is mandatory that the spectral distribution of the source be known or well characterized. Indoor calibration transfers between narrow band radiometers such as Ultraviolet and Photopic detectors shall be accomplished using sources with spectral irradiance distributions as similar as possible to the spectral distribution of the sources to be monitored. This will reduce spectral mismatch errors arising from differences in the spectral response of sensors and dissimilar calibration and 'test' source spectral distributions. In the special case of pyranometers for solar radiation measurements, as long as the reference radiometer has a relatively flat and broad (greater than 700 nm passband) spectral response (for example, black thermopile), or has been calibrated outdoors, the difference between calibration and source spectral distributions is less important, however should be taken into consideration.

4.5 Monitor the output signal of the reference radiometer at the selected data collection interval.

4.6 Ensure the temporal stability of the source, as indicated by the reference radiometer output, has stabilized at reasonable amplitude. Recommended source amplitude for broadband solar radiometers is in the range 500 Wm^{-2} to 1000 Wm^{-2}. For narrowband radiometers, a source amplitude (spectral irradiance distribution integrated over with respect to wavelength over the pass band of the radiometers) of 50% to 125% of the peak amplitude to be expected in the source monitored by the test instruments is recommended.

4.7 The analog voltage signal from each radiometer is measured, digitized, and stored using a calibrated data-acquisition instrument, or system. A minimum of 30 data readings is required.

4.8 The test data are divided by the reference radiometer data, employing the instrument constant of the reference instrument to determine the instrument constant of the radiometer being calibrated. The mean value, the standard deviation, and coefficient of variation are determined.

5. Significance and Use

5.1 The methods described represent a means for calibration of field radiometers employing standard reference radiometers indoors. Other methods involve the natural sunlight outdoors under clear skies, and various combinations of reference radiometers. Outdoor these methods are useful for cosine and azimuth correction analyses, but may suffer from a lack of available clear skies, foreground view factor and directionality problems. Outdoor transfer of calibrations is covered by standards G167, E816, and E824.

5.2 Several configurations of artificial sources are possible, including:

5.2.1 Point sources (lamps) at a distance, to which the sensors are exposed

5.2.2 Extended sources (banks of lamps, or lamp(s) behind diffusing or "homogenizing" screens) to which the sensors are exposed

5.2.3 Various configurations of enclosures (usually spherical or hemispherical) with the interior walls illuminated indirectly with lamps. The sensors are exposed to the radiation emanating from the enclosure walls.

5.3 Traceability of calibration for pyranometers is accomplished when employing the method using a reference global pyranometer that has been calibrated, and is traceable to the World Radiometric Reference (WRR)[4]. For the purposes of this test method, traceability shall have been established if a parent instrument in the calibration chain can be traced to a

[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] Available from Available from International Standards Organization (ISO), 1 Rue De Varembre, Geneva, Switzerland CH-1211 20

[4] WMO—No. 8, "Guide to Meteorological Instruments and Methods of Observation," Fifth Ed., World Meteorological Organization, Geneva, Switzerland, 1983

reference pyrheliometer which has participated in an International Pyrheliometric Comparison (IPC) conducted at the World Radiation Center, (WRC), Davos, Switzerland.

5.3.1 The reference global pyranometer (for example, one measuring hemispherical solar radiation at all wavelengths) shall have been calibrated by the shading-disk, component summation, or outdoor comparison method against one of the following instruments:

5.3.1.1 An absolute cavity pyrheliometer that participated in a World Meteorological Organization (WMO) sanctioned IPC's (and therefore possesses a WRR reduction factor).

5.3.1.2 An absolute cavity radiometer that has been intercompared (in a local or regional comparison) with an absolute cavity pyrheliometer meeting 5.3.1.1.

5.3.1.3 Alternatively, the reference pyranometer may have been calibrated by direct transfer from a World Meteorological Organization (WMO) First Class pyranometer that was calibrated by the shading-disk method against an absolute cavity pyrheliometer possessing a WRR reduction factor, or by direct transfer from a WMO Standard Pyranometer (see WMO's Guide WMO—No. 8 for a discussion of the classification of solar radiometers). See Zerlaut[5] for a discussion of the WRR, the IPC's and their results.

NOTE 4—Any of the absolute radiometers participating in the above intercomparisons and being within ±0.5 % of the mean of all similar instruments compared in any of those intercomparisons, shall be considered suitable as the primary reference instrument.

5.4 Traceability of calibration of narrow band (for example,, Ultraviolet) radiometers is accomplished when employing the method using a reference narrow band radiometer that has been calibrated and is traceable to the National Institute of Standards and Technology (NIST), or other national standards organizations.

5.4.1 The reference narrow band radiometer, regardless of whether it measures total ultraviolet solar radiation, or narrowband UV-A or UV-B radiation, or a defined narrow band segment of ultraviolet radiation, shall have been calibrated by one of the following:

5.4.1.1 By comparison to a standard source of spectral irradiance that is traceable to NIST or to the appropriate national standards organizations of other countries using appropriate filters and filter correction factors [for example, Drummond [6]].

5.4.1.2 By comparison of the radiometer output to the integrated spectral irradiance in the appropriate wavelength band of a spectroradiometer that has itself been calibrated against such a standard source of spectral irradiance,

5.4.1.3 By comparison to a spectroradiometer that has participated in a regional or national Intercomparison of Spectroradiometers, the results of which are of reference quality.

NOTE 5—The calibration of reference ultraviolet radiometers using a spectroradiometer, or by direct calibration against standard sources of spectral irradiance (for example, deuterium or 1000 W tungsten-halogen lamps) is the subject of Standard G138.

5.5 The calibration method employed assumes that the accuracy of the values obtained with respect to the calibration source used are applicable to the deployed environment, with additional sources of uncertainty due to logging equipment and environmental effects above and beyond the calibration uncertainty.

5.6 The principal advantages of indoor calibration of radiometers are user convenience, lack of dependence on weather, and user control of test conditions.

5.7 The principal disadvantages of the indoor calibrations are the possible differences between natural environmental influences and the laboratory calibration conditions with respect to the spectral and spatial distribution of the source radiation (sun and sky versus lamps or enclosure walls).

5.8 It is recommended that the reference radiometer be of the same type as the test radiometer, since any difference in spectral sensitivity between instruments will result in erroneous calibrations. However, The calibration of sufficiently broadband detectors (approximately 700 nm or more), such a silicon photodiode detectors with respect to extremely broadband (more than 2000 nm) thermopile radiometers is acceptable, as long as the additional increased uncertainty in the field measurements, due to spectral response and spectral mismatch limitations, is acceptable. The reader is referred to ISO TR 9673[7] and ISO TR 9901[8] for discussions of the types of instruments available and their use.

6. Interferences

6.1 In order to minimize systematic errors the reference and test radiometers must be as nearly alike in all respects as possible.

6.1.1 The spectral response of both the reference and test radiometers should be as nearly identical as possible.

6.1.2 The spectral content (spectral power distribution) of the calibration source and the source to be monitored in the field experiment should be matched to greatest extent possible. If not, the relative spectral differences should be characterized, reported, and the spectral mismatch characterized.

6.2 Source stability. The measurements selected in determining the instrument constant shall be made during periods of essentially uniform levels or slow (less than 0.5% of full scale per minute) rates of change of radiation (as measured by the reference radiometer). Measurements selected under varying source amplitudes may result in erroneous calibrations if the reference and test radiometers possess significantly different response times.

[5] Zerlaut, G. A., "Solar Radiation Instrumentation," Chapter 5 in Solar Resources, The MIT Press, Cambridge, MA, 1989, pp. 173–308.

[6] Drummond, A.J, and A.K. Ångström, "Derivation of the Photometric Flux of Daylight from Filtered Measurements of Global (Sun and Sky) Radiant Energy", Applied Optics Vol 10 # 9, September 1971.

[7] ISO Technical Report TR 9673, "Solar Radiation and Its Measurement for Determining Outdoor Weathering Exposure Levels," International Standards Organization, Geneva, Switzerland.

[8] ISO/TR 9901:1990, "Solar Energy—Field Pyranometers—Recommended Practice for Use."

6.3 Spatial non-uniformity in the test plane with respect to the location of reference and test detectors will lead to erroneous results, on the order of magnitude of the non-uniformity.

7. Apparatus

7.1 *Data Acquisition Instrument*—A digital voltmeter or data logger capable of repeatability to 0.1 % of average reading, and an uncertainty of ±0.2 % with input impedance of at least 1 MΩ may be employed. Data loggers having printout must be capable of a measurement frequency of at least two per minute. A data logger having three-channel capacity may be useful.

7.2 *Fixed-Angle Calibration Table*—A calibration table/mounting fixture required for all horizontal calibrations.

7.3 *Stable Optical Radiation Source*—A temporally (less than +/- 0.5% of full scale amplitude variation at a sample rate of the 1/e time constant of the reference sensor, or a selected data integration period) and spatially uniform (over the area of sensor(s) exposure) source of optical radiation such as a lamp, bank of lamps, or illuminated enclosure, as described in section 5.2. The spectral distribution of the source must be known over the pass band of the instruments under test. The source characterizations described here need not be accomplished before every calibration, but should be repeated periodically, and especially if calibration data or reference radiometer data show large deviations (more than 2%) from previous or historical results.

7.3.1 Temporal stability is dependent upon the nature of the illumination source; and type of power (uniform direct current, or alternating current) energizing the source.

7.3.1.1 Direct current (DC) powered sources are more stable, but generally of lower power and the required power supply stability requirements at recommended power may increase the source cost significantly

7.3.1.2 Alternating current (AC) powered sources will have inherent fluctuations driven by the alternating current on the order of the period of alternating current. Data captured on an "instantaneous" basis may reflect these fluctuations, especially if fast time response (silicon photodiode) detectors are used. Large (greater than 2%) standard deviations or coefficient of variation (ratio of the standard deviation of the mean to the mean value, expressed as a percentage) in data results may reflect this problem. Integration of data over a large number of AC cycles ("line cycles"), up to several seconds, is recommended to mitigate this problem when using AC powered sources.

7.3.2 Spatial uniformity in the test plane of the sensors is required to assure all sensors are exposed to the same amplitude of radiation during the comparison process. In the following, "signal reference value" means the instantaneous or integrated reference radiometer data as would be recorded during a calibration.

7.3.2.1 Spatial uniformity in the "test plane" of the sensors may be evaluated by recording the maximum difference between an initial (first placement) reference radiometer signal and subsequent placements of the reference radiometer in each test instrument position (until a sample size of at least 20 is reached). The maximum difference between the signal at the starting placement and any other placement should not exceed 1% of the expected (full scale) amplitude.

7.3.2.2 If the test instrument and the reference instrument are replaced in the same location, record the maximum difference between an initial (first placement) of the reference radiometer signal and subsequent removal and re-placements of the reference radiometer in the calibration position. A sample size of at least 20 (removal and replacements) of the reference radiometer are needed. The maximum difference between the signal at the starting placement and any other placement should not exceed 1% of the expected (full scale) amplitude.

7.3.3 The spectral distribution of incandescent, xenon arc, metal halide, light emitting diodes, and other lamp technologies are quite different from each other, and can be more or less representative of the spectral distribution of natural sunlight, or the source to be monitored by the radiometers under calibration. It is required that the spectral distribution of the calibration source be known, measured, or characterized so that it may be compared with the spectral distribution of the source to be measured with the radiometers.

7.3.3.1 The absolute spectral distribution of the calibration source may be measured in the test plane of the radiometers by use of a spectroradiometer system, calibrated in accordance with Standard G138, with the input optic in the test plane.

7.3.3.2 Relative spectral distribution data for lamp sources may be provided by lamp manufacturers; but is suitable only if the range of the spectral response of the sensors under test is encompassed by the spectral data.

7.3.3.3 If the test plane of the radiometers is illuminated indirectly, either by reflection off enclosure (sphere or hemisphere walls), or by radiation transmitted through other optical components, such as mirrors, diffusers, or lenses, the spectral optical properties of the intermediate materials must be known, and the product of the spectral optical properties and spectral distribution data computed to arrive at the radiation spectral distribution at the test plane.

7.3.3.4 The recommended spectral resolution (step size in spectral distribution or spectral optical properties, or both) is 10 nanometers. Digitization or interpolation, or both, of manufacturer supplied spectral data to this resolution is recognized as a valid means of arriving at suitable data for computing the final spectral distribution at the test plane.

8. Procedure

8.1 Mount reference and test radiometers on a common calibration table/fixture in the test plane. Adjust all instruments to a common sensor elevation.

8.2 Connect both the reference and test instruments to their respective, or common, data acquisition instrument, using low capacitance, shielded cable of at least 20 gauge and of identical length for each instrument. Check the instruments for electrical continuity, sign of the signal, and the nominal signal strength and stability. Clean the radiometer's outermost photoreceptive surface (glass dome, filter, window, diffuser, etc.) in accordance with the manufacturer's instructions.

8.3 Adjust the data acquisition system to record data at the selected data collection interval or integration period, or both.

8.4 Measure zero off-sets. Check the off-set signals of both the reference and field radiometers at the start and the end of each measurement series by measuring dark signals before and after use of calibration source by recording simultaneous instantaneous or integrated (as appropriate, consistent with 7.3) with the data logger. Sample sizes of 30 readings are recommended.

8.5 Energize the calibration source and allow the source to stabilize so variations or fluctuations of no more than 0.5% of the operational amplitude of the source, as monitored at the data sample integration period and sample rate from the reference radiometer, occur.

8.6 After the source has stabilized, record instantaneous or integrated voltage readings on both instruments for a minimum of 30 readings. If the reference and test instruments are within the area of +/- 1% spatially uniform radiation, simultaneous recording of reference and test signals is recommended. If instrument position exchange, replacement, or repositioning is used, the time between the position exchanges, and recording of data, should be minimized to the greatest extent possible.

9. Calculations

9.1 *First Step (Instantaneous Readings):*

9.1.1 From each reading i within a measurement series j,(if more than one measurement series is recorderd) calculate the ratio:

$$F(ij) = \frac{V_R(ij)}{V_F(ij)} F_R \tag{1}$$

where:

$V_R(ij)$ and $V_F(ij)$ = the voltages (for example, millivolts) measured using the reference and the field radiometers, respectively

F_R = the calibration factor, for example, watts per square meter per microvolt, of the reference radiometer, which has been adjusted for the typical field conditions, in the case where the field and reference radiometer are of the same type and have the type inherent measurement specification (for instance, in the temperature response). Any other correction functions, such as for cosine response, for the reference radiometer may be used, but the form of the correction must be reported.

9.1.2 When F_R as just defined is not applicable, it is replaced, for each measurement series, by a value of $F_R(j)$ that is fitted to the calibration conditions (for instance, mean temperature) and that gives the most accurate value of irradiance $E(ij)$ according to the following equation:

$$F_R(j) V_R(ij) = E(ij) \tag{2}$$

9.2 *Second Step:*

9.2.1 Determine the series of calibration factors of the field radiometer from n readings of a measurement series j, (if more than one measurement series is recorded) using the following equations:

$$F(j) = \frac{F_R \sum_{n}^{i=1} V_R(ij)}{\sum_{n}^{i=1} V_F(ij)} \tag{3}$$

or

$$F(j) = \frac{F_R [V_R(j)]_{integ}}{[V_F(j)]_{integ}} \tag{4}$$

where:

$[V(j)]_{integ}$ = integrated values.

9.3 *Data Rejection:*

9.3.1 Reject any data that have been subject to operational problems for either the reference or field pyranometer, or radiometer. Also, reject those data for which $F(ij)$ (see Eq 1) deviates by more than ±2 % from $F(j)$ (see Eq 3 or Eq 4). Repeat the calculation of $F(j)$ on the basis of the "clean" data. Compute the final calibration factor in accordance with Eq 5 or Eq 6.

9.4 *Statistical Analysis:*

9.4.1 Determine the stability of the calibration conditions during a measurements series by calculating the standard deviation of $F(ij)$ about their mean for values of the set. For well controlled indoor laboratory sources, coefficient of variation for a series should be less than 1.0% of the mean value.

9.5 *Determination of the Temperature-Corrected Final Calibration Factor:*

9.5.1 If during a measurement series j the temperature T deviates markedly (that is, by more than ±10°C) from the desired typical value T_N, and if the temperature response of the field pyranometer is known to deviate markedly from that of the reference pyranometer, then calculate the final temperature-corrected calibration factor F_{corr} at T_N as follows: First correct the $F(j)$ data using the following equations:

$$F_{corr}(i, T_N) = F(j) \frac{R_T[T(j)]}{R_T(T_N)} \tag{5}$$

and calculate F_{corr} as

$$Fcorr = \frac{1}{m} \sum_{j=1}^{m} F_{corr}(j, T_N) \tag{6}$$

where:

$T(j)$ = the mean air temperature during the measuring series j, in degrees Celsius;

$R_T[T(j)]$ and $R_T(T_N)$ = the responsivities of the field radiometer at $T(j)$ and T_N, respectively,

R = $1/F$.

9.5.2 For pyranometers and ultraviolet radiometers where the temperature coefficients α of the instrument's responsivity are known, adjust the responsivities in accordance with the following:

$$R[T(j)] = [1 + \alpha\,(T(j) - T_N)]R(T_N) \quad (7)$$

9.6 *Determination of the Final Calibration Factor Without Temperature Correction of the Data:*

9.6.1 In cases where it is not necessary or not possible to correct the data relative to the temperature response, derive the final calibration factor of the field pyranometer, or radiometer, from the total number m of measurement series from the following equation:

$$F = \frac{1}{m}\sum_{j=1}^{m} F(j) \quad (8)$$

10. Report

10.1 The report shall state as a minimum the following information:

10.1.1 Radiation source type (Incandescent, Metal Halide, Xenon, etc. lamp)

10.1.2 Source/Sensor geometrical configuration (for example, direct illumination, spherical/hemispherical enclosure without direct illumination, etc.)

10.1.3 Characterization of calibration source spectral distribution relative to the expected spectral distribution for the source to be monitored (for example, Relative spectral distribution plot of source and typical "field" spectrum).

10.1.4 Means of spectral distribution characterization (for example, Spectral measurements, manufacturer specifications)

10.1.5 Test Instrument type (UV-A radiometer, total solar pyranometer, etc.)

10.1.6 Manufacturer and serial number

10.1.7 Reference Instrument Type

10.1.7.1 Reference instrument manufacturer and serial number

10.1.7.2 Reference instrument calibration date and calibration due date

10.1.7.3 Uncertainty statement for reference radiometer responsivity

10.1.8 Date of calibration(s),

10.1.9 Angle(s) of exposure:

10.1.9.1 Angle, (typically, horizontal)

10.1.10 Derived instrument responsivity, V W^{-1} m^{-2} ,or calibration factor, W^{-1} m^{-2} V^{-1}

10.1.11 Temperature mean, °C,

10.1.12 Scale: WRR, NIST spectral irradiance sale, etc.,

10.1.13 Traceability, a concise statement of the hierarchy of traceability including serial numbers of secondary and primary reference instruments

10.1.14 Reference and test instrument wavelength sensitivity band (for example, 300 to 385 nm; or 285 nm to 2500 nm).

11. Precision and Bias

11.1 *Precision*—The precision in determining the instrument constant of a field radiometer is influenced the indoor calibration source character as described in 4.4 and 7.3. Repeatability within any test series performed under stable irradiance conditions should be such that the standard deviation is less than ± 1.0 % of the calibration value of the instrument.

11.1.1 The precision of the derived calibration factor of the test radiometer is influenced by the precision in the calibration factor of the reference standard (radiometer or spectroradiometer) used, the precision of the data logging equipment, and environmental conditions over the series of measurement sessions. This is the transfer precision.

11.1.2 Within-laboratory transfer precision of derived calibration values will vary depending on the stability of the reference standard, range of environmental conditions, source/detector geometry, data selection/exclusion criteria, and sample size for the calibration data set. For instance, the standard deviation of the calibration value (WRR factor) for a reference pyranometer exemplifies the precision for the standard radiometer.

11.1.3 Data for repeated calibrations of radiometers with respect to a reference radiometer or spectroradiometer show within-laboratory precision less than 2.0%, is achievable.

11.2 *Bias*—Bias with respect to WRR or NIST standards will be determined by a combination of the estimated bias in the reference radiometer or spectroradiometer (integrated) data and bias estimates for the data logging equipment. See Section 12 on Uncertainty.

11.3 Between-laboratory bias and precision will be a function of the precision and bias inherent in the respective laboratory reference radiometer or spectroradiometers, combined with the precision and bias estimates for the respective data logging equipment.

11.4 Uncertainties of ±2.0 % can be expected when calibrating radiometers at 0° horizontal based on a reference instrument.

12. Measurement Uncertainty

12.1 Measurement uncertainty is an estimate of the magnitude of systematic and random measurement errors that may be reported along with the measurement errors and measurement results. An uncertainty estimate relates to a particular result obtained by a laboratory carrying out this test method, as opposed to precision and bias statements in Section 11, which were derived from an engineering judgment based on experiences with interlaboratory calibrations.

12.2 It is neither appropriate for, nor the responsibility of this test method to provide explicit values that a user of the method would quote as their estimate of uncertainty. Uncertainty values must be based on data generated by a laboratory reporting results using the method. Measurement uncertainties should be evaluated and expressed according to the NIST guidelines[9] and the ISO Guide to Estimating the Uncertainty in Measurements[10], or "GUM".

12.3 Sources of uncertainty in radiometer calibrations can be divided into broad categories: voltage measurements, reference radiometer performance, solar tracker performance, environmental conditions, and test instrument performance.

[9] B.N. Taylor and C.E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results. NIST Technical Mote 1297, U.S. Government Printing Office, Washington D.C. http://physics.nist.gov/Pubs/guidelines/TN1297/tn1297s.pdf

[10] BIPM, Guide to the expression of uncertainty in measurement. Published by ISO TAG 4, 1993 (corrected and Reprinted 1995) in the name of the BIPM. It is now referred to as the GUM. Its ISBN # is 92-67-10188-9 1995. http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

12.4 Uncertainty in calibration results obtained using this method depend on the calibration uncertainties for the reference instruments used, test instrument performance, and the signal noise encountered during the calibrations.

12.4.1 For reference radiometer data based on spectroradiometric measurements, the uncertainty in the integrated reference irradiance should be reported, based on spectroradiometer uncertainties estimated in accordance with Standard G138.

12.5 One can gather information describing the random uncertainty of a measurement result by repeating the measurements several times and reporting the number of measurements, and their range or standard deviation.

12.6 Averaging over all data will result in larger uncertainties than averaging over selected subsets (such as limited zenith angle, irradiance, or ambient temperature ranges). Therefore a description of the sample subsets used to derive the calibration values and the reported uncertainty estimate is essential.

12.7 *Example Uncertainty:*

The uncertainty in a primary standard pyrheliometer is approximately ±0.3 % (representing 1σ) based on the results of the WMO International Pyrheliometer Comparison since 1980, and seven New River Intercomparisons of Absolute Cavity Pyrheliometers (NRIP's). The mean uncertainty in the transfer of calibration from an absolute cavity pyrheliometer to a secondary standard pyranometer is about ±1.0 %, (2σ) at a specific zenith angle. The total basic uncertainty in the transfer of calibration values between comparable model radiometers is approximately ±2.0 % (2σ) for stable experimental indoor or outdoor conditions with good sky conditions. Transfer uncertainties depend particularly on the relative radiometer cosine responses, thermal offsets, sky conditions, and data logger uncertainty.

12.7.1 According to the GUM, the 2.0% basic uncertainty quoted above is an "expanded uncertainty" (represented by multiplying the "standard" uncertainty of 1.0% by a "coverage factor, k=2), assuming a normal distribution of random errors associated with the calibration and transfer process.

12.7.2 If the calibration factors derived are plotted in a time series, significant bias errors may be discerned. The calibration report should include a statement of the estimated uncertainty based on a combination of reference radiometer uncertainty, standard deviation of the mean calibration value, estimated bias in the data collection process.

13. Keywords

13.1 calibration; field radiometers; pyranometer; Solar radiation; solar radiometer; transfer