Standard Test Method for Transfer of Calibration From Reference to Field Radiometers[1]

This standard is issued under the fixed designation E824; 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 transferring 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 all of the 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 transfer of calibration from reference to field radiometers to be used for measuring and monitoring outdoor radiant exposure levels. This standard has been harmonized with ISO 9847.

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 natural sunshine as the source.

1.4 Calibrations of field radiometers may be performed at tilt as well as horizontal (at 0° from the horizontal to the earth). The essential requirement is that the reference radiometer shall have been calibrated at essentially the same tilt from horizontal as the tilt 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 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 (Test Methods G167 and 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 (Test Method G138).

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

[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.

Current edition approved Dec. 1, 2010. Published December 2010. Originally approved in 1994. Last previous edition approved in 2005 as E824 – 05. DOI: 10.1520/E0824-10.

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

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

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 Standard:*

ISO 9847 Solar Energy—Calibration of Field Pyranometers by Comparison to a Reference Pyranometer[3]

3. Terminology

3.1 *Definitions:*

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

4. Summary of Test Method

4.1 Mount the reference radiometer, or pyranometer, and the field (or test) radiometers, or pyranometers, on a common calibration table for horizontal calibration (Type *A*), on a tilted platform for calibration at tilt (Type *B*), or on an altazimuth or sun-pointing mount for normal-incidence calibration (Type *C*). Adjust the height of the photoreceptor, or radiation receptor, of all instruments to a common elevation.

4.2 Ensure that the pyranometer's, or radiometer's, azimuth reference marks point in a common direction.

NOTE 2—Current convention is to use the electrical connector as the azimuth reference and to point it towards the equator and downward. The reasons are (*1*) this convention diminishes the possibility of moisture intrusion into the connector, and (*2*) it ensures that instruments with disparities in the hemispherical domes, or with domes not properly centered over the receptor, are not operated in such a manner that they amplify deviations from the cosine law.

4.3 For a transfer of calibration to a field instrument that will be used in a tilted position the following conditions must be met: The reference instrument must have a calibration at the desired tilt angle; both instruments must be oriented at the tilt angle and facing the equator.

4.4 The analog voltage signal from each radiometer is measured, digitized, and stored using a calibrated data-acquisition instrument, or system. A minimum of fifteen 10 min measurement sequences are obtained, each sequence comprising a minimum of 21 instantaneous readings. It is preferable that a larger number of measurement sequences be performed over several days duration and that data be taken in early morning or late afternoon, as well as near solar noon.

NOTE 3—Transfer of calibration to both total and narrow-band ultraviolet radiometers may require a larger number of measurement sequences in order to account for spectral changes due to changing air mass both early and late in the day, and to the loss of north-sky ultraviolet when calibrating at tilts.

4.5 The data are mathematically ratioed, employing the instrument constant of the reference instrument to determine the instrument constant of the radiometer being calibrated. The mean value and the standard deviation are determined.

5. Significance and Use

5.1 The methods described represent the preferable means for calibration of field radiometers employing standard reference radiometers. Other methods involve the employment of an optical bench and essentially a point source of artificial light. While these methods are useful for cosine and azimuth correction analyses, they suffer from foreground view factor and directionality problems. Transfer of calibration indoors using artificial sources is not covered by this test method.

5.2 Traceability of calibration of global 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). For the purposes of this test method, traceability shall have been established if a parent instrument in the calibration chain participated in an International Pyrheliometric Comparison (IPC) conducted at the World Radiation Center (WRC) in Davos, Switzerland. Traceability of calibration of narrow- and broad-band radiometers is accomplished when employing the method using a reference ultraviolet radiometer that has been calibrated and is traceable to the National Institute of Standards and Technology (NIST), or other national standards organizations. See Zerlaut[4] for a discussion of the WRR, the IPC's and their results.

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

5.2.1.1 An absolute cavity pyrheliometer that participated in a WMO sanctioned IPC's (and therefore possesses a WRR reduction factor),

5.2.1.2 An absolute cavity radiometer that has been intercompared (in a local or regional comparison) with an absolute cavity pyrheliometer meeting the requirements given in 5.2.1.1.

5.2.1.3 A WMO First Class pyrheliometer that was calibrated by direct transfer from such an absolute cavity.

5.2.2 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

[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 American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

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

transfer from a WMO Standard Pyranometer (see WMO's Guide WMO—No. 8[5] for a discussion of the classification of solar radiometers).

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.

5.2.3 The reference ultraviolet 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:

5.2.3.1 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 filter correction factors),[6]

5.2.3.2 By comparison 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, and

5.2.3.3 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 Test Method G138.

5.3 The calibration method employed assumes that the accuracy of the values obtained are independent of time of year within the constraints imposed by the test instrument's temperature compensation (neglecting cosine errors). The method permits the determination of possible tilt effects on the sensitivity of the test instrument's light receptor.

5.4 The principal advantage of outdoor calibration of radiometers is that all types of radiometers are related to a single reference under realistic irradiance conditions.

5.5 The principal disadvantages of the outdoor calibration method are the time required and the fact that the natural environment is not subject to control (but the calibrations therefore include all of the instrumental characteristics of both the reference and test radiometers that are influenced simultaneously by the environment). Environmental circumstances such as ground reflectance or shading, or both, must be minimized and affect both instruments similarly.

5.6 The reference radiometer must be of the same type as the test radiometer, since any difference in spectral sensitivity between instruments will result in erroneous calibrations. 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 must be as nearly identical as possible.

6.2 *Sky Conditions*—The measurements selected in determining the instrument constant shall be for periods of essentially uniform rates of change of radiation (either cloudless or overcast conditions). Periods selected shall be for 10 to 20 min segments. Measurements selected under varying cloudy conditions may result in erroneous calibrations if the reference and test radiometers possess significantly different response times (see also 5.6).

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 an 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 precision calibration table required for all horizontal and fixed angle tilt tests that is level at 0° horizontal and that is adjustable in tilt over a suitable range of angles from the horizontal.

7.3 *Tracking Calibration Table*—A precision calibration table required for normal incident calibrations and capable of tracking the sun to within ±0.5°.

8. Procedure

8.1 Mount reference and test radiometers on a common calibration table in sunlight. Adjust both instruments to a common elevation facing south for which a calibration value is available. Ensure that the azimuth reference marks point in a common direction: For tilted or tracking calibrations, also ensure that the electrical connector is pointed down (to preclude moisture intrusion), and that it is pointing to the equator (that is, south-facing in the northern hemisphere) if used as the azimuth reference.

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

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

[6] Angstrom, A. K., and Drummond, A. J. "Fundamental Principles and Methods for the Calibration of Radiometers for Photometric Use," *Applied Optics*, Vol 1, No. 4 , July 1962, pp. 455-464.

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

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

surface (glass dome, filter, window, diffuser, etc.) in accordance with the manufacturer's instructions. Check that the radiant fluxes of the foreground on both instruments are equal at the relevant tilt angle by transposing the positions of at least two of the most widely separated radiometers.

8.3 Take particular care to measure for 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 carefully covering the photoreceptor with an opaque, light-tight shield.

8.4 For stable, cloudless sky conditions, simultaneously take instantaneous voltage readings on both instruments for a minimum of fifteen 10 to 20 min measurement sequences each consisting of 21 instantaneous readings. Take these data sets over a 2 to 3-day period. Ensure that the data are taken from near sunrise through and including solar noon, to sunset during the test period. Do not include data taken at zenith angles greater than 70° (at sun elevations below 20°).

8.5 For less than stable, cloudless sky conditions, simultaneously take instantaneous voltage readings on both instruments continuously at from 1 to 5 min intervals from early morning to late afternoon for a minimum of 5 days (and as long as 2 weeks). The length of time should be such that fifteen 21-point data sets are obtained that represent steady radiation and that span sunrise to sunset.

9. Calculations

9.1 *First Step (Instantaneous Readings):*

9.1.1 From each reading i within a measurement series j, 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 pyranometers, respectively, and

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 function, 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 using the following equations:

$$F(j) = \frac{\sum_{i=1}^{n} F(i,j)}{n} \tag{3}$$

or

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

where:

$[V(j)]_{\text{integ}}$ = 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 measurement series by calculating the coefficient of variance (standard deviation divided by the mean) for the values in the set.

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:

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

and calculate F_{corr} as

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

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, and

each R = $1/F$ from equation 3 or 4.

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:

$$R[T(j)] = [1 + \alpha(T(j) - T_N)] R(T_N) \tag{7}$$

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 Instrument type,

10.1.2 Manufacturer and serial number,

10.1.3 Reference instrument type,

10.1.3.1 Reference instrument manufacturer and serial number,

10.1.3.2 Reference instrument calibration date and calibration due date,

10.1.3.3 Uncertainty statement for reference radiometer,

10.1.4 Date of calibration(s),

10.1.5 Angles of exposure:

10.1.5.1 Angle,

10.1.5.2 Instrument constant, V W^{-1} m^{-2} ,

10.1.5.3 Range of solar time,

10.1.5.4 Relative humidity (average), %, and

10.1.5.5 Temperature mean, °C,

10.1.6 Scale: WRR, etc.,

10.1.7 Latitude, longitude, and altitude,

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

10.1.9 Reference and test instrument wavelength sensitivity band (that is, 300 to 385 nm).

11. Precision and Bias

11.1 *Precision*—The precision in determining the instrument constant of a field radiometer is influenced by sky conditions, and particularly by variations in cosine response when performing measurements at low solar elevations. Repeatability within any 21-value test scan performed at or near solar noon under stable irradiance conditions should be such that the standard deviation is less than ±0.5 % 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, solar 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 over a specified, limited zenith angle range (30 to 60°).

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 over reasonably limited ranges of zenith angle.

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 interlaboratory study.

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.

12.3 Measurement uncertainties should be evaluated and expressed according to the NIST guidelines[9] and the ISO Guide to Estimating the Uncertainty in Measurements as distributed in by the American National Standards Institute.[10]

12.4 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.

12.5 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.

12.5.1 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 Test Method G138.

12.6 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.

[9] Taylor, B. N., and Kuyatt, C. E., Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Tech Note 1297, U.S. Government Printing Office, Washington D.C., 1994. Available on the world wide web at http://physics.nist.gov/Pubs/guidelines/TN1297/tn1297s.pdf

[10] American National Standards Institute (ANSI), American National Standard for Expressing Uncertainty—U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997. Secretariat, National Conference of Standards Laboratories (NSCL), Boulder, CO, 1997.

12.7 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.

12.8 *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 experimental conditions with good sky conditions. Transfer uncertainties depend particularly on the relative radiometer cosine responses, thermal offsets, sky conditions, and data logger uncertainty.

12.8.1 According to the ISO Guide, 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.

12.8.2 If the calibration factors derived are plotted in a time series or versus zenith angle, 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