Standard Test Method for
Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers[1]

This standard is issued under the fixed designation E816; 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 measurement of the direct (beam) radiation component of sunlight are required in *(1)* the calibration of reference pyranometers by the shading disk or optical occluding methods, *(2)* determination of the energy collected by concentrating solar collectors, including exposure levels achieved in use of Practice G90 dealing with Fresnel-reflecting concentrator test machines, and *(3)* the assessment of the direct beam for energy budget analyses, geographic mapping of solar energy, and as an aid in the determination of the concentration of aerosol and particulate pollution, and water vapor effects.

This test method requires calibration to the World Radiometric Reference (WRR), maintained by the World Meteorological Organization (WMO), Geneva. The Intercomparison of Absolute Cavity Pyrheliometers, also called Absolute Cavity Radiometers, on which the WRR depends, is covered by procedures adopted by WMO and by various U.S. Organizations who occasionally convene such intercomparisons for the purpose of transferring the WRR to the United States, and to maintaining the WRR in the United States. These procedures are not covered by this test method.

1. Scope

1.1 This test method has been harmonized with, and is technically equivalent to, ISO 9059.

1.2 Two types of calibrations are covered by this test method. One is the calibration of a secondary reference pyrheliometer using an absolute cavity pyrheliometer as the primary standard pyrheliometer, and the other is the transfer of calibration from a secondary reference to one or more field pyrheliometers. This test method prescribes the calibration procedures and the calibration hierarchy, or traceability, for transfer of the calibrations.

NOTE 1—It is not uncommon, and is indeed desirable, for both the reference and field pyrheliometers to be of the same manufacturer and model designation.

1.3 This test method is relevant primarily for the calibration of reference pyrheliometers with field angles of 5 to 6°, using as the primary reference instrument a self-calibrating absolute cavity pyrheliometer having field angles of about 5°. Pyrheliometers with field angles greater than 6.5° shall not be designated as reference pyrheliometers.

1.4 When this test method is used to transfer calibration to field pyrheliometers having field angles both less than 5° or greater than 6.5°, it will be necessary to employ the procedure defined by Angstrom and Rodhe.[2]

1.5 This test method requires that the spectral response of the absolute cavity chosen as the primary standard pyrheliometer be nonselective over the range from 0.3 to 10 µm wavelength. Both reference and field pyrheliometers covered by this test method shall be nonselective over a range from 0.3 to 4 µm wavelength.

1.6 The primary and secondary reference pyrheliometers shall not be field instruments and their exposure to sunlight shall be limited to calibration or intercomparisons. These reference instruments shall be stored in an isolated cabinet or room equipped with standard laboratory temperature and humidity control.

NOTE 2—At a laboratory where calibrations are performed regularly, it is advisable to maintain a group of two or three secondary reference pyrheliometers that are included in every calibration. These serve as controls to detect any instability or irregularity in the standard reference pyrheliometer.

1.7 This test method is applicable to calibration procedures using natural sunshine only.

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[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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[2] Angstrom, A., and Rodhe, B., "Pyrheliometric Measurements with Special Regard to the Circumsolar Sky Radiation," *Tellus*, Vol 18, 1966, pp. 25–33.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E772 Terminology of Solar Energy Conversion

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

G90 Practice for Performing Accelerated Outdoor Weathering of Nonmetallic Materials Using Concentrated Natural Sunlight

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

2.2 *ISO Standards:*[4]

ISO 9059 Calibration of Field Pyrheliometers by Comparison to a Reference Pyrheliometer

ISO 9060 Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation

ISO TR 9673 The Instrumental Measurement of Sunlight for Determining Exposure Levels

ISO 9846 Calibration of a Pyranometer Using a Pyrheliometer

2.3 *WMO Standard:*

Guide to Meteorological Instruments and Methods of Observation, Seventh ed., WMO-No. 8[5]

3. Terminology

3.1 *Definitions:*

3.1.1 The relevant definitions of Terminology E772 apply to the calibration method described in this test method.

3.1.2 *absolute cavity pyrheliometer*—see *self-calibrating absolute cavity pyrheliometer*.

3.1.3 *direct radiation, direct solar radiation, and direct (beam) radiation*—radiation received from a small solid angle centered on the sun's disk, on a given plane whose normal (perpendicular to the plane) points to the center of the sun's disk (see ISO 9060). That component of sunlight is the beam between an observer, or instrument, and the sun within a solid conical angle centered on the sun's disk and having a total included planar field angle of, for the purposes of this test method, 5 to 6°.

3.1.4 *field pyrheliometer*—pyrheliometers that are designed and used for long-term field measurements of direct solar radiation. These pyrheliometers are weatherproof and therefore possess windows, usually quartz, at the field aperture that pass all solar radiation in the range from 0.3 to 4 µm wavelength.

3.1.5 *opening angle*—with radius of field aperture denoted by *R* and the distance between the field and receiver apertures denoted by *l*, the opening angle is defined for right circular cones by the equation:

$$Z_o = \tan^{-1} R/l \qquad (1)$$

The field angle is double the opening angle.

3.1.6 *primary standard pyrheliometers*—pyrheliometers, selected from the group of absolute pyrheliometers (see *self-calibrating absolute cavity pyrheliometer*).

3.1.7 *reference pyrheliometer*—pyrheliometers of any category serving as a reference in calibration transfer procedures. They are selected and well-tested instruments (see Table 2 of ISO 9060), that have a low rate of yearly change in responsivity. The reference pyrheliometer may be of the same type, class, and manufacturer as the field radiometers in which case it is specially chosen for calibration transfer purposes and is termed a secondary standard pyrheliometer (see ISO 9060), or it may be of the self-calibrating cavity type (see *self-calibrating absolute cavity pyrheliometer*).

3.1.8 *secondary standard pyrheliometer*—pyrheliometers of high precision and stability whose calibration factors are derived from primary standard pyrheliometers. This group comprises absolute cavity pyrheliometers that do not fulfill the requirements of a primary standard pyrheliometer as described in 3.1.6.

3.1.9 *self-calibrating absolute cavity pyrheliometer*—a radiometer consisting of either a single- or dual-conical heated cavity that, during the self-calibration mode, displays the power required to produce a thermopile reference signal that is identical to the sampling signal obtained when viewing the sun with an open aperture. The reference signal is produced by the thermopile in response to the cavity irradiance resulting from heat supplied by a cavity heater with the aperture closed.

3.1.10 *slope angle*—with radius of the sensor denoted by *r*, the radius of the limiting aperture is denoted by *R*, and the distance between aperture and sensor denoted by *l*, the slope angle equation is defined as:

$$S = \mathrm{arcTan}\,(R - r)/l \qquad (2)$$

3.2 *Acronyms:*

3.2.1 *ACR*—Absolute Cavity Radiometer

3.2.2 *ANSI*—American National Standards Institute

3.2.3 *ARM*—Atmospheric RadiationMeasurement Program

3.2.4 *DOE*—Department of Energy

3.2.5 *GUM*—(ISO) Guide to Uncertainty in Measurements

3.2.6 *IPC*—International Pyrheliometer comparison

3.2.7 *ISO*—International Standards Organization

3.2.8 *NCSL*—National Council of Standards Laboratories

3.2.9 *NIST*—National Institute of Standards and Technology

3.2.10 *NREL*—National Renewable Energy Laboratory

3.2.11 *PMOD*—Physical Meteorological Observatory Davos

3.2.12 *SAC*—Singapore Accreditation Council

3.2.13 *SINGLAS*—Singapore Laboratory Accreditation Service

3.2.14 *UKAS*—United Kingdom Accrediation Service

3.2.15 *WRC*—World Radiation Center

3.2.16 *WRR*—World Radiometric Reference

3.2.17 *WMO*—World Meteorological Organization

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[3] 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.

[4] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

[5] Available from World Meterological Organization, 7bis, avenue de la Paix, CP. 2300, CH-1211 Geneva 2, Switzerland, www.wmo.int.

4. Significance and Use

4.1 Though the sun trackers employed, the number of instantaneous readings, and the data acquisition equipment used will vary from instrument to instrument and from laboratory to laboratory, this test method provides for the minimum acceptable conditions, procedures, and techniques required.

4.2 While the greatest accuracy will be obtained when calibrating pyrheliometers with a self-calibrating absolute cavity pyrheliometer that has been demonstrated by intercomparison to be within ±0.5 % of the mean irradiance of a family of similar absolute instruments, acceptable accuracy can be achieved by careful attention to the requirements of this test method when transferring calibration from a secondary reference to a field pyrheliometer.

4.3 By meeting the requirements of this test method, traceability of calibration to the World Radiometric Reference (WRR) can be achieved through one or more of the following recognized intercomparisons:

4.3.1 International Pyrheliometric Comparison (IPC) VII, Davos, Switzerland, held in 1990, and every five years thereafter, and the PMO-2 absolute cavity pyrheliometer that is the primary reference instrument of WMO.[6]

4.3.2 Any WMO-sanctioned intercomparison of self-calibrating absolute cavity pyrheliometers held in WMO Region IV (North and Central America).

4.3.3 Any sanctioned or non-sanctioned intercomparison held in the United States the purpose of which is to transfer the WRR from the primary reference absolute cavity pyrheliometer maintained as the primary reference standard of the United States by the National Oceanic and Atmospheric Administration's Solar Radiation Facility in Boulder, CO.[7]

4.3.4 Any future intercomparisons of comparable reference quality in which at least one self-calibrating absolute cavity pyrheliometer is present that participated in IPC VII or a subsequent IPC, and in which that pyrheliometer is treated as the intercomparison's reference instrument.

4.3.5 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.

4.4 The calibration transfer method employed assumes that the accuracy of the values obtained are independent of time of year and, within the constraints imposed, time of day of measurements. With respect to time of year, the requirement for normal incidence dictates a tile angle from the horizontal that is dependent on the sun's zenith angle and, thus, the air mass limits for that time of year and time of day.

5. Interferences

5.1 *Radiation Source*—Transfer of calibration from reference to secondary standard or field pyrheliometers is accomplished by exposing the two instruments to the same radiation field and comparing their corresponding measurands. The direct irradiance should not be less than 300 $W \cdot m^{-2}$, but irradiance values exceeding 700 $W \cdot m^{-2}$ is preferred.

5.2 *Sky Conditions*—The measurements made in determining the instrument constant shall be performed only under conditions when the sun is unobstructed by clouds for an incremental data-taking period. The most acceptable sky conditions should be such that the direct irradiance is not less than 80 % of the hemispherical irradiance measured with a pyranometer aligned with its axis vertical and calibrated in accordance with Test Method G167. Also, no cloud formation may be within 15° of the sun during the period data are taken for record when either transferring calibration to a secondary standard pyrheliometer (to be used as a reference pyrheliometer) from an absolute cavity pyrheliometer, or when transferring calibration from a secondary reference pyrheliometer to field pyrheliometers. Generally, good calibration conditions exist when the cloud cover is less than 12.5 %.

NOTE 3—Contrails of airplanes that are within 15° of the sun can be tolerated providing the ratio of so affected measurements to unaffected measurements is small in any series.

NOTE 4—Atmospheric water vapor in the pre-condensation phase occasionally causes variable atmospheric transmission. Generally, the scattering of measuring data that is produced by these clusters is acceptable.

5.2.1 The atmospheric turbidity during transfer of calibration should be close to values typical for the field measuring conditions. Generally, the turbidity should be confined to conditions with Linke turbidity factors lower than six (see ISO 9059 and ISO 9060).

5.2.2 The circumsolar radiation (aureole) originates from forward scattering of direct solar radiation. It decreases from the limb of the sun to an angular distance of about 15° by several orders of magnitude, depending on the type and concentration of the aerosol.[2,8,9] The typical amount of circumsolar radiation within an angular distance of 5° of the sun represents only a few percent of the direct solar radiation. If standard and field pyrheliometers have different field-of-view angles, the aerosol may strongly influence the accuracy of the transfer of calibration. Calculated percentages of circumsolar contained in direct solar radiation, for different aerosol types and solar elevation angles, are given for information in Appendix X1.

5.3 *Differences in Geometry*—If the pyrheliometers being compared do not have similar opening angles, atmospheric turbidity will introduce errors into the calibration.[2]

5.4 *Wind Conditions*—Wind conditions are known to affect instruments differently, particularly some self-calibrating absolute cavity pyrheliometers, particularly when the wind is blowing from the direction of the sun's azimuth (±30°). Measurements affected by wind conditions should be rejected. A tolerable maximum wind speed for unprotected measurement conditions cannot be specified.

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[6] WRCD, "Results, Seventh International Pyrheliometer Comparisons," *Working Report No. XX*, Swiss Meteorological Institute, Zurich, Switzerland, Month, 1991.

[7] Currently (2005) the TMI/Kendall Absolute Cavity Radiometer, SN 67502 and Eppley Laboratory Model AHF SN 28553.

[8] Eiden, R., " Calculations and Measurements of the Spectral Radiance of the Solar Aureole," *Tellus* , Vol 20, No. 3, 1968, pp. 380–399.

[9] Thomalla, E., Köpke, P., Müller, H., and Quenzel, H., "Circumsolar Radiation Calculated for Various Atmospheric Conditions," *Solar Energy*, Vol 30, No. 6, 1983, pp. 575–587.

NOTE 5—Pyrheliometers with open apertures will yield lower measured values and a higher standard deviation under adverse wind conditions. The magnitude of these effects depends on the type and design of the diaphragms in the pyrheliometer tube. Wind effects may be reduced by installing wind screens or insulating blankets around the tube, or both.

6. Apparatus

NOTE 6—For a discussion of the various types of equipment, apparatus and instruments required in practicing this test method, reference is made to ISO 9060, ISO TR 9673, and Zerlaut.[10]

6.1 *Sun Tracker(s),* whether a clock-driven equatorial mount or a servo-operated altazimuth mount, to maintain both the reference and the field (test) pyrheliometer normal to the sun for the entire test period.[11] Equatorial and altazimuth astronomical and specially constructed sun-following mounts may also be used. However, the admissible misalignment of the sun tracker shall be maintained less than the slope angle (S) of the pyrheliometer minus 0.25°.

NOTE 7—For a discussion of the various types of equipment, apparatus and instruments required in practicing this test method, reference is made to ISO 9060, ISO TR 9673, and Zerlaut.[10]

6.2 *Self-Calibrating Absolute Cavity Pyrheliometer,* employed as the primary standard pyrheliometer, when used as the reference pyranometer to calibrate secondary standard pyrheliometers, shall be selected in accordance with the criteria presented in 3.1.3 and the hierarchy presented in Annex A1.[12]

6.3 *Secondary Standard (Reference) Pyrheliometer,* employed as the reference pyrheliometer for the purposes of transferring calibration to field pyrheliometers shall be of suitable quality in terms of linearity and stability of its instrument constant, sensitivity, and temperature compensation that it meets or exceeds the specifications of a WMO High Quality/ISO First Class Pyrheliometer in accordance with ISO 9060 and WMO No. 8.[13]

6.3.1 The principal additional requirement is that it shall have been calibrated within six months by the procedures presented in this test method using a self-calibrating absolute cavity pyrheliometer as the primary standard.

6.4 *Digital Electronic Readout (for Data Acquisition),* a digital voltmeter, or data logger, capable of resolution repeatable to 0.05 % of the maximum pyrheliometer reading, with an input impedance with an input impedance of at least 1 MΩ and an uncertainty of ±0.2 % of at least 1 MΩ. Data loggers must have the capability of recording, or printing, a measurement with a frequency of every 30 s, or better, and shall be stable over a period of at least one year, including temperature-generated drift, of better than ±0.1 %.

6.4.1 The data logger should have at least a four-channel capacity and shall have the capacity to synchronously capture data from all channels within 1 s. If the data logger is capable of delivering integrated pyrheliometer signals, the minimum integration time shall not be longer than about 10 min.

7. Procedure

7.1 *Transfer of Calibration from Primary to Secondary Standard Reference Pyrheliometers:*

7.1.1 Mount the self-calibrating absolute cavity pyrheliometer, hereinafter designated the primary standard, and the secondary reference pyrheliometer to be calibrated, hereinafter designated the secondary standard, either together or separately on one or two sun-tracking mounts. Ensure that the alignment is within less than 0.5° from true in accordance with either 7.1.1.1 or 7.1.1.2. If separate mounts are used, ensure that the distance between pyrheliometers is not greater than 20 m.

NOTE 8—Large distances between instruments can influence results because of the inhomogeneity of the direct irradiance due to structured turbidity elements in the atmosphere.

7.1.1.1 If the tracker is an equitorial mount, align the trackers in azimuth to coincide with solar noon (south reference) and in elevation to coincide with the local latitude. Align the pyrheliometers coaxially with the solar line-of-sight using the diopters or other mechanisms provided.

7.1.1.2 If the tracker is an altazimuth mount, set the tracking mechanism and ensure that the pyrheliometer is aligned with its axis perpendicular to the plane of the tracking platform using the diopters or other mechanisms provided.

7.1.2 Connect each instrument to its respective, or common, digital voltmeter, or data logger. Check for electrical continuity, sign of the signal, and normal signal strength and stability.

7.1.2.1 Allow at least 30 min for the pyrheliometers to reach temperature equilibrium with ambient. Allow a minimum 30 min warm-up of the data logger and the control unit of the absolute cavity pyrheliometer prior to taking measurements. Ensure that both the data logger, or digital voltmeter, and the primary standard pyrheliometer's control unit are shaded from direct sunlight.

7.1.3 If required, install wind screens around and in front of the pyrheliometers, or an insulating blanket, to preclude high-velocity winds from impacting the aperture areas and tubes of the pyrheliometers. This may be doubly important when performing calibration transfers under winter-time conditions.

7.1.4 Using the diopters or sighting mechanisms provided, perform alignment checks and adjustments of both pyrheliometers when necessary prior to the commencement of data taking.

7.1.5 Clean the quartz aperture of the secondary reference pyrheliometer. Also, clean the quartz aperture of the primary standard reference pyrheliometer if it is provided with a cover.

7.1.6 Calibrate the primary standard in accordance with the manufacturer's instructions.

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[10] Zerlaut, G. A., "Solar Radiation Instrumentation," Chapter 5, *Solar Resources*, R. L. Hulstron, ed., MIT Press, Cambridge, MA, 1989, pp. 173–308.

[11] Suitable trackers are manufactured by the Eppley Laboratories, Inc., 12 Sheffield Ave., Newport, RI 02840, and Kipp and Zonen USA, 390 Central Avenue, Bohemia, NY 11716.

[12] Suitable self-calibrating absolute cavity pyrheliometers are the Eppley Model HF manufactured by The Epply Laboratories, Inc., Newport, RI 02840, the TMI Mark VI manufactured by Technical Measurements, Inc. Box 838, LaCanada, CA 91011, and the PMO-6 and later series of absolute radiometers available from Compagnie Industrielle Radioelectrique, Switzerland.

[13] Suitable secondary reference pyrheliometers are the Eppley Model NIP manufactured by The Eppley Laboratory (see Footnote 13), and the EKO Instruments Model MS-53 available from SC-International Inc., 346 W. Pine Valley Drive, Phoenix, AZ and EKO Instruments Trading Co., Ltd., 21-8 Hatagaya 1-chome, Shibuya-ku, Tokyo 151 JAPAN.

7.1.7 Record the output voltages from the secondary standard (the test instrument) and the irradiance obtained from the primary standard with all measurements made within a 1 s interval. Record data each 30 s for 21 readings obtained over a 10 min test span, or at least one integrated value over each 10 min test span. Take not less than six test spans at high irradiance levels centered about solar noon on each of three days. Preferably, include an additional test span on each day, both 2 h on each side of solar noon.

NOTE 9—If the characteristics of the primary standard instrument require a measurement interval greater than 30 s, the measurement interval may be increased providing the measurements in each pair are simultaneous and the total number of measurements is not diminished.

NOTE 10—If it is desirable or necessary to determine the dependence of calibration factors on parameter values such as temperature, turbidity, solar elevation, and so forth, carry out a larger number of measuring series than specified above. In this case, the results may be correlated with the parameter of interest using, simply, linear regression analysis.

7.1.8 Determine the standard deviations of the measured values from the reference and from the field instrument within each series and between the average values of each series in order to determine the reliability of the data recorded.

7.1.9 Record all operational problems as well as any special environmental conditions observed during the measurements.

7.2 *Transfer of Calibration from Secondary Reference to Field Pyrheliometers:*

7.2.1 Mount the secondary standard pyrheliometer and the field pyrheliometer, or pyrheliometers, either together on a common or on separate sun-following mounts. Align the trackers in accordance with the procedure provided in 7.1.1.

7.2.2 Take the same premeasurement precautions, and perform the same steps, prior to taking measurements as described in 7.1.2 through 7.1.5.

7.2.3 Record the zero offset of all pyrheliometers included in the calibration transfer measurement sequences by covering their apertures. Wait for ten time constants prior to recording the offset signals; also, wait for a minimum of ten time constants prior to taking data after removal of the covers.

7.2.4 Record test data and other pertinent information in accordance with the requirements of 7.1.7 through 7.1.9.

8. Interpretation of Results

8.1 *Determination of Calibration Factors:*

8.1.1 From each reading, *i*, within a measuring series, *j*, calculate:

$$F(i,j) = \frac{E_{SP}(i,j)}{V_{FP}(i,j)} \tag{3}$$

where:

$E_{SP}(i, j)$ = irradiance values of direct solar radiation given by the reference pyrheliometer (whether the primary or secondary standard), and

$V_{FP}(i, j)$ = signals of the test pyrheliometer (whether the secondary standard or field pyrheliometer), with the zero offset subtracted prior to manipulation of Eq 3.

8.1.2 Determine the preliminary calibration factor, $F(j)$, of the field pyrheliometer from the *n* readings of a measuring series, *j*, using the following formula:

$$F(j) = \frac{\sum_{i=1}^{n} F(i,j)}{n} \tag{4}$$

8.1.3 Derive the final calibration factor, *F*, of the test pyrheliometer (whether it is the secondary standard or a field pyrheliometer) from the total number, *m*, of measuring series (for example, spans) using the formula given by Eq 5:

$$F = \frac{1}{m}\sum_{j=1}^{m} F(j) \tag{5}$$

8.2 *Data Rejection:*

8.2.1 If data were captured, or recorded, that resulted from conditions subject either to undesirable sky conditions, or operational problems, reject the corresponding data from all pyrheliometers. Refer to Gregoire[14] for additional discussion of rejection criteria.

8.2.2 Also, reject the data if $F(k, j)$ from Eq 1 deviates by more than ±2 % from $F(j)$, obtained from Eq 3.

NOTE 11—According to experience, a deviation of 2 % indicates a disturbed value.

8.3 *Analysis:*

8.3.1 As a measure of the sensitivity of the pyrheliometer, or pyrheliometers, to irradiance level and the concomitant sky conditions attendant thereto, evaluate the values of $F(j)$ for measuring series, or spans, taken at low irradiance levels. Record the differences in values of *F*, the calibration factor of the instrument(s), for such nonideal conditions.

8.3.2 As a measure of the stability of the calibration conditions during a measuring series, determine the standard deviation of the $F(k, j)$ values from the $F(j)$ values. Determine the standard deviation of the $F(j)$ values from the *F* values. These represent the stability of the instrument and of the conditions during the entire calibration period.

9. Report

9.1 Report the following information:

9.1.1 *Certificate of Calibration*—The certificate shall state as a minimum the following information:

9.1.2 The calibration method, citing this test method,

9.1.3 Instrument type,

9.1.4 Manufacturer, model number, and instrument serial number,

9.1.5 A concise statement of the traceability of the calibration factor of the reference pyrheliometer in relation to the primary standard pyrheliometer, and the WRR reduction factor of the self-calibrating primary standard shall be given,

9.1.6 Dates of calibration and the latitude, longitude, and altitude of the site,

9.1.7 The number of evaluated single measurements and the number of measuring days over which the data were collected,

9.1.8 The calibration conditions, that is, the range of mean air temperature, the range of solar elevation angles (and the apparent air mass values, if easily computed), the range of turbidity (for example, the Linke turbidity factor) and the range

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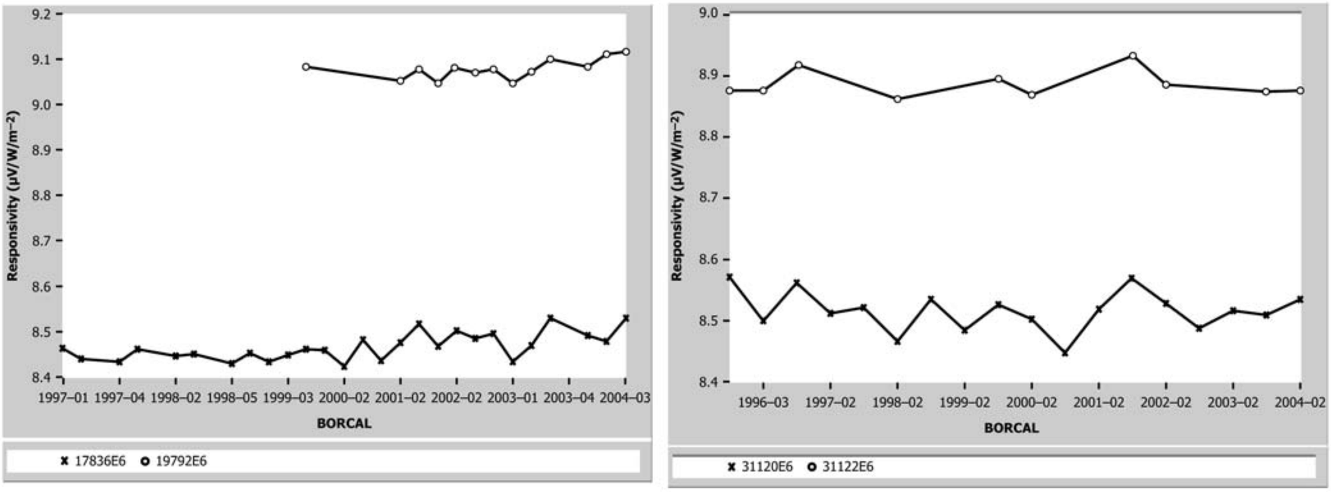
[14] Gregoire, P., "Pyrheliometer Comparison," *Trappes: Meteorologie Nationale S.E.T.I.M.*, 1984.

and arithmetic mean value of the wind speed, and the range of irradiances measured, and



NOTE 1—Each graph shows repeated calibration results for two pyrheliometers.

FIG. 1 Typical Within Laboratory Precision for Lab A (left) and Lab B (right) for Pyrheliometer Calibrations

9.1.9 The results of the derived calibration value expressed either as watts per square metre per volt ($W \cdot m^{-2} \cdot V^{-1}$), or as volts per watts per square metre ($V \cdot W^{-1} \cdot m^{2}$).

9.1.10 A statement of the estimated uncertainty in the resulting calibration value, and a description of how the uncertainty was arrived at. (i.e., standard deviation of results, range of results, zenith angle restrictions, etc.).

9.2 *Records and Record Retention*—The data that shall be recorded, and maintained by the calibration facility for the life of the instrument, shall, in addition to that required in 10.1, include the following:

9.2.1 All raw data,

9.2.2 All computations,

9.2.3 Solar time for all data sets,

9.2.4 Ambient temperature, wind velocity and direction, and percent relative humidity for all data sets, and

9.2.5 All observations of sky conditions, whether measured using a sun photometer or recorded in terms of technical descriptions, and any unusual events, operational problems, and so forth.

10. Precision and Bias

10.1 The precision of the derived calibration factor of the field or secondary standard reference pyrheliometer is influenced by the precision in the calibration factor of the reference standard used, the precision of the data logging equipment, and environmental conditons This is the transfer precision.

10.1.1 Within laboratory transfer precision of derived calibration values will vary depending on the stability of the reference pyrheliometer (primary or secondary), 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 primary reference absolute cavity radiometer exemplifies the precision for the primary reference pyrheliometer.

10.1.2 Data for repeated calibrations of pyrheliometers with respect to a primary reference pyrheliometer show within laboratory precision of better than 1.0 % is achievable (see Fig. 1 and Table 2).

10.1.3 Between laboratory transfer precision for primary reference pyrheliometers (self calibrating electrical substitution radiometers) has been reported to be less than 0.05 % (see Table 1).

TABLE 1 Between Laboratory Precision for Transfer of WRR to Primary Reference (Self-Calibrating Electrical Substitution) Pyrheliometers

	Ratios to WRR Factor		
	IPC – IX[A]	Local IPC	Percent Difference
Inst A	0.99733	0.99713	0.02
Inst B	1.00026	1.00043	0.02
Inst C	0.99866	0.99839	0.03
Inst D	0.99846	0.99835	0.01
Inst E	0.99861	0.99829	0.03
Inst F	0.99966	1.00076	0.11
Inst G	0.99848	0.99810	0.04
	Average Difference (%)		0.04

[A] Anonymous, International Pyrheliometer Comparison IPC-IX 2000 Results and Symposium, Working Report No. 197. Swiss Meteorological Institute, Davos and Zurich, Switzerland, May 2001.

10.1.4 Published reports of uncertainty analysis for field pyrheliometer calibrations show the transfer precision of pyrheliometer calibration values within a laboratory are on the

TABLE 2 Within and Between Laboratory Precision and Bias for Pyrheliometer Calibrations at Two Laboratories

				Between	Within	Within
1 Event		2 Lab A Rs	3 Lab B Rs	4 Delta Lab A-Lab B	5 Delta Lab A	6 Delta Lab B
	1	8.896				
	2	8.942			0.52	
	3		8.922	0.22		
	4	8.929		0.08	0.15	
	5		8.878	0.57		0.49
Inst A	6	8.860		0.20	0.77	
	7		8.899	0.44		0.24
	8		8.881			0.20
	9	8.897		0.18	0.42	
	10		8.933	0.40		0.59
	11		8.851			0.92
	12	8.803		0.55	1.06	
	13		8.872	0.78		0.24
	14		8.876			0.05
	15	8.642				
	16	8.569			0.84	
	17		8.551	0.21		
	18		8.490			0.71
	19		8.509			0.22
Inst B	20	8.490		0.22	0.92	
	21		8.555	0.77		0.54
	22		8.500			0.64
	23		8.495			0.06
	24		8.477			0.21
	25		8.491			0.17
	26		8.478			0.15
	27		8.477			0.01
		Coefficient of Variation		Mean % Bias	0.67	0.34
Precision Inst A		0.57	0.34			
Precision Inst B		0.89	0.34	0.39		

order of 0.5 % for an individual calibration value within a period of 10 minutes.[15]

10.1.5 Data for repeated calibrations of pyrheliometers with respect to a primary reference pyrheliometer show between laboratory precision of less than 1.0 % (see Table 2).

10.2 Bias in the derived calibration factor of the field or secondary standard pyrheliometer will be influenced by systematic measurement uncertainty components in the transfer process, including systematic errors in the primary or secondary reference pyrheliometer. Traceability of the primary or secondary reference pyrheliometer to the World Radiometric Reference (WRR) implies bias estimates are with respect to WRR.

10.2.1 Within laboratory bias estimates will vary with data logging equipment performance and environmental conditions (such as aerosol optical depth and consequent circumsolar radiation, wind, ambient temperature).

10.2.2 Published reports of uncertainty analysis for field pyrheliometer calibrations[15] show the estimated bias from one calibration to another (between laboratories) for pyrheliometer calibration values are on the order of 1.0 % for an individual calibration value.

10.2.3 Data for repeated calibrations of pyrheliometers with respect to a primary reference pyrheliometer show average between laboratory biases of less than 1.0 % (see Table 2).

10.2.4 For the data in Table 2, Laboratory A and Laboratory B exchanged two instruments (A and B) periodically over a nine year period (1996–2004) and reported the indicated calibration values. Column 1 is the calibration event number. Col 2 is the reported calibration value (Responsivity, Rs, uV/W/m^{-2}) from laboratory A. Column 3 is the reported calibration value (Rs) from laboratory B. Column 4 is the absolute value of the percent difference between adjacent calibration Rs values expressed as a percent of the earliest Rs value in the pair. Columns 5 and 6 are the absolute value of the percent difference between adjacent calibration Rs values within a laboratory expressed as a percent of the earliest Rs value in the pair. At the bottom of the table, the standard deviations of all calibrations within a laboratory are expressed as a percentage of the mean calibration within each laboratory (Columns 2 and 3). At the bottom of column 4 is the average bias between laboratories in percent. At the bottom of columns 5 and 6 is the average bias between adjacent calibrations within each laboratory expressed in percent. All sample sizes in the calibration events were greater than 1000. Data in Table 2 is a compilation of 27 calibrations conducted (and documented in twenty three Broadband Outdoor Radiometer Calibration Reports) at the National Renewable Energy Laboratory, Golden, CO. and the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program Central Calibration Facility in Lamont, OK.

11. Measurement Uncertainty

11.1 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

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[15] Myers, D. R., Reda, I., Wilcox, S., and Andreas, A., "Optical Radiation Measurements for Photovoltaic Applications: Instrumentation Uncertainty and Performance," *49th Annual Conference of the Society of Photo-optical Instrumentation Engineers*, Organic Photovoltaics V. 2004. Denver, CO: SPIE Bellingham, Washington.

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 10, which were derived from an interlaboratory study.

11.2 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.

11.3 Measurement uncertainties should be evaluated and expressed according to the NIST guidelines[16] and the ISO Guide to Estimating the Uncertainty in Measurements published in the U.S. by the American National Standards Institute.[17]

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

11.5 Uncertainty in calibration results obtained using this method depend on the calibration uncertainties of the instruments used and the signal noise encountered during the calibrations.

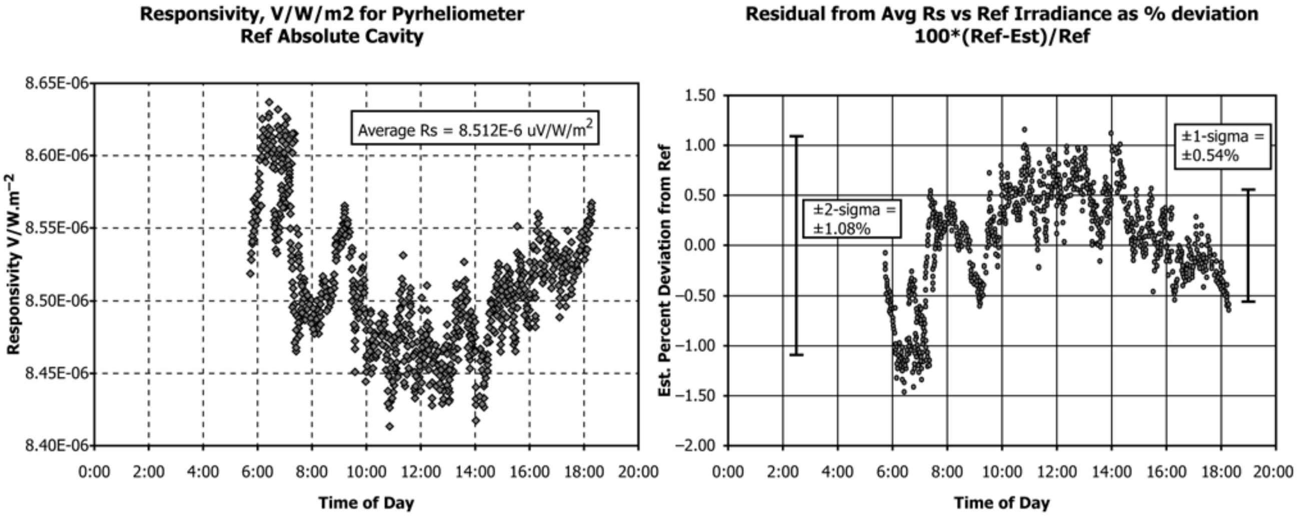
11.6 One can gather information describing the random uncertainty of a measurement result by repeating the measurements several times and reporting the number of measurements, and their range or standard deviation.

11.7 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.

11.8 The uncertainty in the primary standard pyrheliometer is approximately ±0.3 % (representing 1σ) based on the results of the WMO International Pyrheliometer Comparison conducted 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 pyrheliometer is about ±0.3 % (1σ) making the total basic uncertainty in the calibration value for the secondary standard approximately ±0.5 % (1σ) for experimental conditions with good sky conditions. The transfer uncertainties depend particularly on the circumsolar radiation and the view angle of the pyrheliometers.

11.8.1 According to the ISO Guide, the 0.5 % total basic uncertainty quoted above is a "standard uncertainty" (represented as one standard deviation). Assuming a normal distribution of errors associated with the calibration and transfer process, the "expanded uncertainty" is computed by multiplying the "standard" uncertainty by a "coverage factor, k = 2" as described in the reference in footnote 17. Then the total expanded uncertainty in the calibration and transfer process = 2 × 0.5 = 1.0 %.

11.8.2 The total basic uncertainty derived in 11.8 assumes that the uncertainty in the primary standard pyrheliometer and



NOTE 1—Responsivity of test pyrheliometer in volts per watt per square meter in left panel. Average of all Rs = $8.5125 \cdot 10^{-6}$ V w^{-1} m^{-2}. The standard deviation of the average Rs is $4.58 \cdot 10^{-8}$, or 0.54 % of the mean Rs. Applying the mean responsivity to the pyrheliometer calibration data voltages, compute the percent difference between the reference irradiance and the estimate of the irradiance based on the average Rs (right panel). Note the difference between the pyrheliometer based estimate and the reference irradiance ranges from –1.5 to +1.0 %. By computing the expanded uncertainty with a coverage factor of 2, the expanded uncertainty = 2·0.54 = 1.08 %, which encompasses 95 % of the percent deviations seen in the right panel.

FIG. 2 Uncertainty Example

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[16] 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.

[17] 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.

the transfer process from the primary standard to the secondary standard include the 0.1 % uncertainty allowed in the data logging equipment and transfer process (tracking, stable environmental conditions, etc.).

11.8.3 If the calibration factors derived are plotted in a time series or versus zenith angle, bias errors greater than the 0.5 % total basic uncertainty may be discerned. The calibration report should include a statement of the estimated uncertainty and a brief description of how the estimate was determined (see 9.1.10).

11.9 If the total calibration uncertainty is presumed to be ±0.5 % for the secondary standard pyrheliometer, and the transfer error is also ±0.5 % for the field pyrheliometers, the total basic uncertainty in the calibration value of field radiometers will be approximately ± 0.75 % for good sky conditions and reasonable circumsolar radiation.

11.9.1 As in 11.8.1, the total expanded uncertainty, with coverage factor k = 2 for the transfer from a secondary standard pyrheliometer = 2 × 0.75 = 1.5 %.

11.9.2 As in 11.8.2, the total basic uncertainty in the transfer of calibration from the secondary standard to the field pyrheliometer is assumed to contain the 0.1 % data logger uncertainty. If the data logger uncertainty is greater than 0.1 %, the total basic uncertainty in the transfer will be greater.

11.9.3 The statement in 11.8.3 applies as well to the transfer of calibration from a secondary reference to a field pyrheliometer. The calibration report shall include an estimate of uncertainty in the reported calibration value, and a brief description of how the estimate was obtained.

11.10 Fig. 2 illustrates an estimate of measurement uncertainty derived from calibration data. Note the example does not include sources of uncertainty from the calibration reference or data logger performance, but only the statistical variation of the calibration value in the calibration process. The 1.08 % expanded uncertainty derived in the example must be combined with the expanded uncertainty arising from the reference pyrheliometer, data logger, and environmental conditions.

ANNEX

(Mandatory Information)

A1. CALCULATED PERCENTAGES OF CIRCUMSOLAR RADIATION CONTAINED IN DIRECT SOLAR RADIATION

A1.1 Table A1.1 gives an overview of the possible effect of aerosols on the relative contribution of circumsolar radiation $E_{s,rel}$ (α) to the irradiance of direct solar radiation measured by means of pyrheliometers with different field-of-view angles α (see ISO 9060).

A1.2 Four types of aerosol (urban, continental (background), maritime, and desert) and three values (0.05, 0.2, and 0.4) of the spectral optical thickness δ_p (λ = 550 nm) that are respective measures of a low, medium, and high total amount of aerosol particles are considered; the corresponding spectral Linke turbidity factors T (λ = 550 nm) are approximately 1.8, 3.4, and 5.4.

A1.3 The percentages of circumsolar radiation given are for solar elevation angles γ = 60° and γ = 20°.

APPENDIX

(Nonmandatory Information)

X1. HIERARCHY OF EXISTING STANDARDS, CALIBRATION, AND TRACEABILITY

TABLE A1.1 Circumsolar Radiation Values for Various Atmospheric Conditions[9]

Aerosol			γ	E_s (α = 32') W·m^{-2} (sun disk)	$E_{s,rel}$ (α) %		
Type	δ_p (λ = 550 nm)	T (λ = 550 nm)			α = 5°	α = 10°	α = 20°
Urban	0.05	1.8	60°	985	0.1	0.2	0.5
	0.20	3.4		872	0.3	0.7	1.7
	0.40	5.4		746	0.5	1.3	3.1
	0.05	1.8	20°	736	0.1	0.5	1.2
	0.20	3.4		555	0.5	2.6	3.9
	0.40	5.4		389	1.2	2.9	6.9
Continental (background)	0.05	1.8	60°	979	0.4	0.6	1.0
	0.20	3.4		851	0.8	2.1	3.7
	0.40	5.4		707	1.8	4.1	7.3
	0.05	1.8	20°	725	0.7	1.4	2.6
	0.20	3.4		514	2.4	5.1	9.3
	0.40	5.4		328	4.1	9.8	17.6
Maritime	0.05	1.8	60°	972	0.7	1.2	1.8
	0.20	3.4		826	2.8	4.6	6.8
	0.40	5.4		668	5.2	9.1	13.4
	0.05	1.8	20°	711	1.6	2.9	4.5
	0.20	3.4		473	6.6	11.5	17.1
	0.40	5.4		275	12.9	22.7	33.6
Desert	0.05	1.8	60°	979	...	0.4	0.9
	0.20	3.4		852	...	1.4	3.1
	0.40	5.4		708	...	2.7	6.1
	0.05	1.8	20°	724	...	0.9	2.2
	0.20	3.4		511	...	3.4	7.7
	0.40	5.4		325	...	6.5	14.5

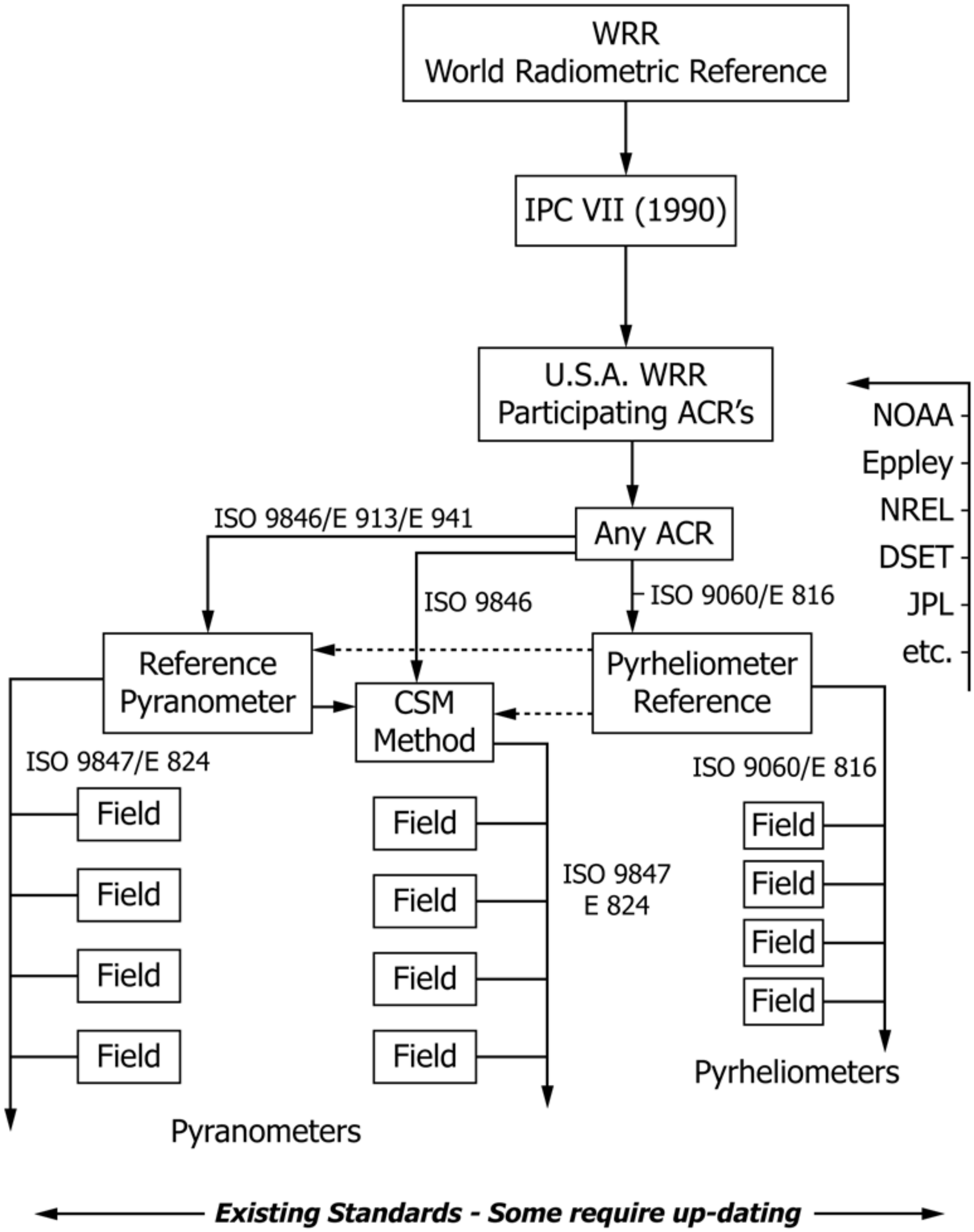

FIG. X1.1 Hierarchy of Existing Standards, Calibration, and Traceability

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