Designation: G167 – 15

Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer[1]

This standard is issued under the fixed designation G167; 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 global (hemispherical) solar irradiance are required in the assessment of irradiance and radiant exposure in the testing of exposed materials, determination of the energy available to solar collection devices, and assessment of global and hemispherical solar radiation for meteorological purposes.

This test method requires calibrations traceable to the World Radiometric Reference (WRR), which represents the SI units of irradiance. The WRR is determined by a group of selected absolute pyrheliometers maintained by the World Meteorological Organization (WMO) in Davos, Switzerland.

Realization of the WRR in the United States, and other countries, is accomplished by the intercomparison of absolute pyrheliometers with the World Radiometric Group (WRG) through a series of intercomparisons that include the International Pyrheliometric Conferences held every five years in Davos. The intercomparison of absolute pyrheliometers is covered by procedures adopted by WMO and is not covered by this test method.

It should be emphasized that "calibration of a pyranometer" essentially means the transfer of the WRR scale from a pyrheliometer to a pyranometer under specific experimental procedures.

1. Scope

1.1 This test method covers an integration of previous Test Method E913 dealing with the calibration of pyranometers with axis vertical and previous Test Method E941 on calibration of pyranometers with axis tilted. This amalgamation of the two methods essentially harmonizes the methodology with ISO 9846.

1.2 This test method is applicable to all pyranometers regardless of the radiation receptor employed, and is applicable to pyranometers in horizontal as well as tilted positions.

1.3 This test method is mandatory for the calibration of all secondary standard pyranometers as defined by the World Meteorological Organization (WMO) and ISO 9060, and for any pyranometer used as a reference pyranometer in the transfer of calibration using Test Method E842.

1.4 Two types of calibrations are covered: Type I calibrations employ a self-calibrating, absolute pyrheliometer, and Type II calibrations employ a secondary reference pyrheliometer as the reference standard (secondary reference pyrheliometers are defined by WMO and ISO 9060).

1.5 Calibrations of reference pyranometers may be performed by a method that makes use of either an altazimuth or equatorial tracking mount in which the axis of the radiometer's radiation receptor is aligned with the sun during the shading disk test.

1.6 The determination of the dependence of the calibration factor (calibration function) on variable parameters is called characterization. The characterization of pyranometers is not specifically covered by this method.

1.7 This test method is applicable only to calibration procedures using the sun as the light source.

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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E772 Terminology of Solar Energy Conversion

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

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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] 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.

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2.2 *WMO Document:*[3]

World Meteorological Organization (WMO), "Measurement of Radiation" Guide to Meteorological Instruments and Methods of Observation, seventh ed., WMO-No. 8, Geneva

2.3 *ISO Standards:*[4]

ISO 9060:1990 Solar Energy—Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation

ISO 9846:1993 Solar Energy—Calibration of a Pyranometer Using a Pyrheliometer

3. Terminology

3.1 *Definitions:*

3.1.1 See Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *altazimuth mount, n*—a tracking mount capable of rotation about orthogonal altitude and azimuth axes; tracking may be manual or by a follow-the-sun servomechanism.

3.2.2 *calibration of a radiometer, v*—determination of the responsivity (or the calibration factor, the reciprocal of the responsivity) of a radiometer under well-defined measurement conditions.

3.2.3 *direct solar radiation, n*—that component of solar radiation within a specified solid angle (usually 5.0° or 5.7°) subtended at the observer by the sun's solar disk, including a portion of the circumsolar radiation.

3.2.4 *diffuse solar radiation, n*—that component of solar radiation scattered by the air molecules, aerosol particles, cloud and other particles in the hemisphere defined by the sky dome.

3.2.5 *equatorial mount, n*—see Terminology E772.

3.2.6 *field of view angle of a pyrheliometer, n*—full angle of the cone which is defined by the center of the receiver surface (see ISO 9060, 5.1) and the border of the limiting aperture, if the latter are circular and concentric to the receiver surface; if not, effective angles may be calculated (**1, 2**).[5]

3.2.7 *global solar radiation, n*—combined direct and diffuse solar radiation falling on a horizontal surface; solar radiation incident on a horizontal surface from the hemispherical sky dome, or from 2π Steradian (Sr).

3.2.8 *hemispherical radiation, n*—combined direct and diffuse solar radiation incident from a virtual hemisphere, or from 2π Sr, on any inclined surface.

3.2.8.1 *Discussion*—The case of a horizontal surface is denoted *global solar radiation* (3.2.7).

3.2.9 *pyranometer, n*—see Terminology E772.

3.2.10 *pyranometer, field, n*—a pyranometer meeting WMO Good Quality or better (that is, High Quality) appropriate to field use and typically exposed continuously.

3.2.11 *pyranometer, reference, n*—a pyranometer (see also ISO 9060), used as a reference to calibrate other pyranometers, which is well-maintained and carefully selected to possess relatively high stability and has been calibrated using a pyrheliometer.

3.2.12 *pyrheliometer, n*—see Terminology E772 and ISO 9060.

3.2.13 *pyrheliometer, absolute (self-calibrating), n*—a solar radiometer with a limited field of view configuration. The field of view should be approximately 5.0° and have a slope angle of from 0.75 to 0.8°, with a blackened conical cavity receiver for absorption of the incident radiation. The measured electrical power to a heater wound around the cavity receiver constitutes the method of self-calibration from first principles and traceability to absolute SI units. The self-calibration principle relates to the sensing of the temperature rise of the receiving cavity by an associated thermopile when first the sun is incident upon the receiver and subsequently when the same thermopile signal is induced by applying precisely measured power to the heater with the pyrheliometer shuttered from the sun.

3.2.14 *shading-disk device, n*—a device which allows movement of a disk in such a way that the receiver of the pyranometer to which it is affixed, or associated, is shaded from the sun. The cone formed between the origin of the receiver and the disk subtends an angle that closely matches the field of view of the pyrheliometer against which it is compared. Alternatively, and increasingly preferred, a sphere rather than a disk eliminates the need to continuously ensure the proper alignment of the disk normal to the sun. See Appendix X1.

3.2.15 *slope angle, n*—the angle defined by the difference in radii of the view limiting aperture (radius = R) and the receiver radius (= r) in a pyrheliometer. The slope angle, s, is the arctangent of R minus r divided by the distance between the limiting aperture and the receiver surface, denoted by L: $s = \mathrm{Tan}^{-1}(R - r)/L$. See Ref (**1**).

3.2.16 *thermal offset, n*—a non-zero signal generated by a radiometer when blocked from all sources of radiation. Believed to be the result of infrared (thermal) radiation exchanges between elements of the radiometer and the environment.

3.3 *Acronyms:*

3.3.1 *ACR*—Absolute Cavity Radiometer

3.3.2 *ANSI*—American National Standards Institute

3.3.3 *ARM*—Atmospheric RadiationMeasurement Program

3.3.4 *DOE*—Department of Energy

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

3.3.6 *IPC*—International Pyrheliometer comparison

3.3.7 *ISO*—International Standards Organization

3.3.8 *NCSL*—National Council of Standards Laboratories

3.3.9 *NIST*—National Institute of Standards and Technology

3.3.10 *NREL*—National Renewable Energy Laboratory

3.3.11 *PMOD*—Physical Meteorological Observatory Davos

3.3.12 *SAC*—Singapore Accreditation Council

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[3] Available from World Meterological Organization, 7bis, avenue de la Paix, CP2300, CH-1211 Geneva 2, Switzerland, http://www.wmo.int.

[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] The boldface numbers in parentheses refer to the list of references at the end of this standard.

3.3.13 *SINGLAS*—Singapore Laboratory Accreditation Service

3.3.14 *UKAS*—United Kingdom Accrediation Service

3.3.15 *WRC*—World Radiation Center

3.3.16 *WRR*—World Radiometric Reference

3.3.17 *WMO*—World Meteorological Organization

4. Significance and Use

4.1 The pyranometer is a radiometer designed to measure the sum of directly solar radiation and sky radiation in such proportions as solar altitude, atmospheric conditions and cloud cover may produce. When tilted to the equator, by an angle β, pyranometers measure only hemispherical radiation falling in the plane of the radiation receptor.

4.2 This test method represents the only practical means for calibration of a reference pyranometer. While the sun-trackers, the shading disk, the number of instantaneous readings, and the electronic display equipment used will vary from laboratory to laboratory, the method provides for the minimum acceptable conditions, procedures and techniques required.

4.3 While, in theory, the choice of tilt angle (β) is unlimited, in practice, satisfactory precision is achieved over a range of tilt angles close to the zenith angles used in the field.

4.4 The at-tilt calibration as performed in the tilted position relates to a specific tilted position and in this position requires no tilt correction. However, a tilt correction may be required to relate the calibration to other orientations, including axis vertical.

NOTE 1—WMO High Quality pyranometers generally exhibit tilt errors of less than 0.5 %. Tilt error is the percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1000 W·m^{23}.

4.5 Traceability of calibrations to the World Radiometric Reference (WRR) is achieved through comparison to a reference absolute pyrheliometer that is itself traceable to the WRR through one of the following:

4.5.1 One of the International Pyrheliometric Comparisons (IPC) held in Davos, Switzerland since 1980 (IPC IV). See Refs **(3-7)**.

4.5.2 Any like intercomparison held in the United States, Canada or Mexico and sanctioned by the World Meteorological Organization as a Regional Intercomparison of Absolute Cavity Pyrheliometers.

4.5.3 Intercomparison with any absolute cavity pyrheliometer that has participated in either and IPC or a WMO-sanctioned intercomparison within the past five years and which was found to be within ±0.4 % of the mean of all absolute pyrheliometers participating therein.

4.6 The calibration method employed in this test method assumes that the accuracy of the values obtained are independent of time of year, with the constraints imposed and by the test instrument's temperature compensation circuit (neglecting cosine errors).

5. Selection of Shade Method

5.1 *Alternating Shade Method:*

5.1.1 The alternating shade method is required for a primary calibration of the reference pyranometer used in the Continuous, Component-Summation Shade Method described in 5.2.

5.1.2 The pyranometer under test is compared with a pyrheliometer measuring direct solar irradiance (or, optionally, a continuously shaded control pyranometer; see Appendix X3 – Appendix X5). The voltage values from the pyranometer that correspond to direct solar irradiance are derived from the difference between the response of the pyranometer to hemispherical (unshaded) solar irradiance and the diffuse (shaded) solar irradiance. These response values (for example, voltages) are induced periodically by means of a movable sun shade disk. For the calculation of the responsivity, the difference between the unshaded and shaded irradiance signals is divided by the direct solar irradiance (measured by the pyrheliometer) component that is normal to the receiver plane of the pyranometer.

5.1.3 For meteorological purposes, the solid angle from which the scattered radiative fluxes that represent diffuse radiation are measured shall be the total sky hemisphere, excluding a small solid angle around the sun's disk.

5.1.4 In addition to the basic method, modifications of this method that are considered to improve the accuracy of the calibration factors, but which require more operational experience, are presented in Appendix X3 – Appendix X5.

5.2 *Continuous Sun-and-Shade Method (Component Summation):*

5.2.1 The pyranometer is compared with two reference radiometers, one of which is a pyrheliometer and the other a well-calibrated reference pyranometer equipped with a tracking shade disk or sphere to measure diffuse solar radiation. The reference pyranometer shall be either calibrated using the alternating sun-and shade method described in 5.1, or shall be compared against such a pyranometer in accordance with Test Method E824.

5.2.2 Global solar irradiance (or hemispherical solar irradiance for inclined pyranometers) is determined by the sum of the direct solar irradiance measured with a pyrheliometer multiplied by the cosine of the incidence angle of the beam to the local horizontal (or inclined plane parallel to the radiometer sensor), plus the diffuse solar irradiance measured with a shaded reference pyranometer mounted in the same configuration (tilted or horizontal) as the unit under test.

5.2.3 The smallest uncertainty realized in the calibration of pyranometers will occur when the pyrheliometer is a self-calibrating absolute cavity pyrheliometer and when the reference pyranometer has itself been calibrated over a range of air mass (zenith angle) by the component summation (continuous shade) method using a reference diffuse pyranometer with a minimal thermal offset (see 6.1). Such a reference pyranometer must have been calibrated under conditions in which the continuously shaded pyranometer had been itself calibrated by the alternating shade method.

5.3 *Comparison of the Alternating and Continuous Shade Methods:*

5.3.1 A disadvantage of the continuous, or component-summation shade method, is that two radiometers must be employed as reference: a pyrheliometer and a continuously shaded pyranometer.

5.3.2 A disadvantage of the component-summation method is the complexity of the apparatus to effect a continuously moving, that is, tracking, shaded disk/sphere with respect to the reference pyranometer's receiver.

5.3.3 An advantage of the component-summation method is that any number of co-planer pyranometers may be calibrated at the same time.

5.3.4 Calibrations performed using the component-summation method have the advantage of much lower uncertainties under conditions of moderately high to high ratios of direct to diffuse solar radiation.

NOTE 2—If an absolute pyrheliometer with a typical uncertainty of 0.5 % is used to measure the direct solar radiation when the direct component is 80 % of the global radiation (as an example), and a pyranometer with an uncertainty of 4 % is used to measure 20 % of the horizontal diffuse solar radiation, resultant uncertainties can be as low as 1.2 % (as opposed to nearly 4 % for the alternating shade method).

6. Interferences and Precautions

6.1 *Pyranometer Design and Thermal Performance*—The absolute accuracy of the calibration of thermal detector (thermopile) pyranometers depends on the design of the detector of the unit under test and the design of the detector of the pyranometer measuring the diffuse irradiance in the component-summation technique.

6.1.1 Pyranometers with thermal sensing elements (thermopiles) have two basic designs: all black detectors, and black and white detectors. In the former, reference junctions for the thermopile are not exposed to solar radiation, and measuring junctions are under a black coating exposed to the solar radiation. In the latter, the measuring (under black coatings) and reference (under white coatings) junctions are exposed to the same solar and thermal radiation environment.

6.1.2 Pyranometers with all black detectors have inherent thermal imbalance, referred to as thermal offset, which is dependent on the exchange of radiation between the detector, protective domes, and the sky hemisphere (**8-12**). These offsets range from equivalent irradiance levels of –5 Wm^{-2} to -25 Wm^{-2}, depending on climatic and meteorological conditions.

6.1.3 Some all-black detector pyranometers are designed with compensating thermopiles to reduce the thermal offset signal to the lower limits (–5 Wm^{-2}) mentioned in 6.1.2, however the offset is never entirely eliminated in those designs (**10**, **11**).

6.1.4 Pyranometers with black-and-white detectors have substantially reduced thermal offsets, in the range of –2 Wm^{-2} or less (**9**, **10**).

6.1.5 In consequence of 6.1.1 to 6.1.4, the most accurate diffuse irradiance measurement for the component summation technique is that made with a black-and-white detector design for the diffuse reference pyranometer.

6.1.6 The calibrations of pyranometers with all-black detectors with an all-black detector reference pyranometer for diffuse measurement in the component summation technique, will have inherently larger uncertainties, due to the unknown magnitudes of thermal offset voltages in the all-black detectors (**10**, **11**).

6.1.7 Pyranometers utilizing solid-state photoconductive or photovoltaic detectors (for example, silicon photodiodes) have limited spectral response ranges (typically only about 75 % of the full solar spectrum), non uniform spectral response, and varying temperature and angular response characteristics, depending on their design. These factors should be considered as additional sources of uncertainty, and included in the uncertainty analysis of results for calibrations of and measurements from such pyranometers. See Section 15, Measurement Uncertainty.

NOTE 3—Because of extreme differences in the spectral power distribution of total hemispherical and diffuse hemispherical solar radiation, the use of pyranometers with detectors that have limited spectral response, such as silicon photodiodes, to measure diffuse irradiance can produce errors of up to several percent in diffuse irradiance (shaded configuration). Thus the alternating shade method of calibration for silicon detector pyranometers, and the use of such radiometers to measure a diffuse reference irradiance is discouraged.

6.2 *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 minimum acceptable direct solar irradiance on the tilted surface, given by the product of the pyrheliometer measurement and the cosine of the incident angle, shall be 80 % of the global solar irradiance. Also, no cloud formation shall be within 30° of the sun during the period that data are taken for record.

6.3 *Instrument Orientation Corrections*—The irradiance calibration of a pyranometer is influenced by the tilt angle and the azimuthal orientation of the instrument about its optical axis. Orientation effects are minimized by using an altazimuth platform and mounting the tilted pyranometer with the cable connection mounted pointing downward. When calibrating a pyranometer with its axis vertical, the sun angle changes through a range of azimuths. Hence, the azimuth angle between the sun and the direction of the cable connector or other reference mark may be significant.

6.3.1 Pyranometers with black-and-white detectors possess a pattern of alternating reference and measuring thermojunctions that significantly affect the azimuthal response of these instruments.

6.3.2 For maximum accuracy in the alternating shade calibration of pyranometers with black-and-white detectors, rotation of the radiometer to at least six different azimuths, in increments of 60°, is required (**12**, **13**). See Appendix X4.

6.4 *Cosine Corrections*—This test method permits the pyranometer to be tested either with axis vertical (with the pyranometer mounted in an exactly horizontal plane), or with the axis directed toward the sun by employing an altazimuth platform. With the pyranometer's axis vertical, the zenith and incident angles are the same and never smaller than:

$$z = L - \delta \quad (1)$$

where:

z = the zenith (or incident angle),

L = the latitude of the site, and
δ = the solar declination for the day.

6.4.1 The range of minimum incident angles available for test due to the range of latitudes available in the continental U.S. is 2.4 and 24.6° at the summer solstice, and 49.2 and 71.4° at the winter solstice, for Miami and Seattle, respectively. The flux calibration is derived from flux measurements made at incident angles of convenience but referred to the value the calibration would have if the measured flux were incident at a specific incidence angle selected by the user (usually 45°). Therefore, since each calibration involves the cosine and azimuth correction of the pyranometer at each incident angle, the accuracy of the calibration is limited by the cosine and azimuth correction uncertainty. (See Note 8 and Note 12, Sections 10 and 10.3.4.)

6.4.2 When the pyranometer is calibrated with its axis pointing toward the sun, there are no cosine errors either during calibration or during use as a transfer instrument in the tilted mode. The incident angles and hence the cosine corrections should be quantified as "usually less than 1%."

6.4.3 When the pyranometer is calibrated at a fixed tilt from the horizontal (and at a fixed azimuth direction), the calibration factor includes the instrument constant and the cosine and azimuth correction of the pyranometer at each incident angle. The accuracy of the calibration is therefore limited by the cosine and azimuth correction uncertainty.

6.5 *Environmental Conditions*—Under general conditions of both calibration and use, the pyranometer signal is a function of many parameters, which may affect calibration factors or data derived from use to a significant degree. Many of these parameters are beyond the scope of this test calibration method and the control of the practitioner.

6.6 *Reference Radiometers*—Both the reference pyrheliometer or pyranometer(s) shall not be used as a field instrument and its exposure to sunlight shall be limited to calibration or to intercomparisons.

NOTE 4—At a laboratory where an absolute cavity pyrheliometer is not available, it is advisable to maintain a group of two or there pyrheliometers which are included in every calibration. These serve as controls to detect any instability or irregularity in any of the reference instruments. It is also advisable to maintain a set of two or three reference pyranometers for the same reasons.

6.6.1 Reference radiometers shall be stored in such a manner as to not degrade their calibration. Exposure to excessive temperature or humidity can cause instrumental drift.

6.6.2 The distance between the reference radiometer(s) and the field pyranometer(s) being calibrated shall be no more than 30 m, otherwise both the reference and field radiometers may not be similarly affected by the same atmospheric events such as, for example, structured turbidity elements.

6.7 *Physical Environment*—Precautions shall be taken to ensure that the horizon is substantially free of natural or manmade objects that obscure more than 5 % of the sky at the horizon. Special emphasis shall be given to ensure that any objects that do exist above the horizon do not reflect an additional strong direct beam (specular) component onto the test units. It is recommended that the foreground at the calibration facility be as similar to the foreground where tilted instruments are to be deployed as possible.

6.7.1 During calibration, wind conditions are also important, since absolute cavity pyrheliometers operating with open apertures may be disturbed by strong wind speeds, especially gusts coming from the sun's azimuthal direction. Under such conditions, it may be necessary to operate with wind screens or insulating jackets, or both, around the pyrheliometer tube if wind-induced instability of the measurements is significant.

7. Apparatus

7.1 *Adjustable Platform*—For calibrations performed with the pyranometer's axis vertical, a level platform is required (all field pyranometers to be calibrated are expected to possess spirit levels for final leveling). For calibrations performed with the pyranometer's axis tilted to the equator, a platform adjustable in azimuth and tilt from the horizontal with an accuracy of greater than 0.5° shall be employed.

7.2 *Digital Microvoltmeter*—Any digital microvoltmeter with a precision of ±0.1 % of the average reading, and an uncertainty of ±0.1 % of the radiometers' calculated outputs at 1100 Wm^{-2}. A data logger having at least three-channel capacity is required for the alternating shade method, while the continuous shade, or component summation, method requires three channels for the reference radiometers and as many additional channels as there are field pyranometers being calibrated. High temperature stability is required for outdoor operation. The data sampled from all radiometers should be recorded within about 1 s. A time resolution for calculating the corresponding solar elevation angle with an uncertainty of less than 0.1° is required. For documenting the variation of the measured values during the calibration, the data shall be appropriately recorded.

7.3 *Field Pyranometer*—In principle, this method can be applied to any type of pyranometer.

7.4 *Reference Pyranometer*—Pyranometer(s) that are either WMO/High Quality, ISO/First Class, ISO/Secondary Standard, or possess characteristics that are intermediate between First Class and Secondary Standard pyranometers, in terms of the requirements of ISO 9060 and the WMO Guide to Meteorological Instruments and Methods of Observation (**1**).

7.5 *Primary Standard Pyrheliometer*—A self-calibrating absolute cavity pyrheliometer designated by the WMO Guide to Meteorological Instruments and Methods of Observation (**1**) and ISO 9060 as a primary standard, and intended for use in Type I calibrations.

NOTE 5—Self-calibrating absolute cavity pyrheliometers generally have unobstructed apertures, that is, the cavity receiver is open to the atmosphere. Hence, no question arises concerning the spectral transmission of window materials.

7.6 *Reference Pyrheliometer*—A pyrheliometer used to perform Type II calibrations that meets the WMO Guide to Meteorological Instruments and Methods of Observation (**1**) for WHO/High Quality and ISO 9060 specifications for a Secondary Standard, or First Class Pyrheliometer, and selected depending on the accuracy of calibration transfer required.

7.7 *Solar Tracker*[6]—A solar tracker is required for normal incident calibrations, that is, with the pyranometers optical axis pointing to the sun. The tracker may be manually operated providing it possesses a sun-pointing alignment device that is accurate to ±0.3°. When an altazimuth tracking mount is employed, which is the preferable method, it must have a tracking accuracy of ±0.5°. An altazimuth tracking mount is mandatory for pyrheliometers whose responsivity over the receiver surface is not circular-symmetrical. Servo-operated bi-directional azimuth and altitude trackers (altazimuth) are available.

7.8 *Shade Disk Apparatus*—Regardless of whether the alternating- or the continuous-shade methods are used for calibration, the geometry of the disk/sphere with respect to the pyranometer's receiver surface (and transparent glass dome) are the same.

7.8.1 *Requirements:*

7.8.1.1 The shade disk/sphere shall be positioned perpendicular to the sun's ray and at a fixed distance *d* from the center of the receiver surface of the pyranometer.

7.8.1.2 The radius *r* of the shade disk or sphere should be larger than the radius of the optical receiver, diffuser, or protective dome of the pyranometer by a minimum of $d \tan(0.5°)$, where d is the distance from the pyranometer receiver to the shade device, to allow for the divergence of the sun's beam and for small tracking errors.

7.8.1.3 The ratio *r/d*, where *r* is the radius of the shade device, should define an angle at the center of the pyranometer's receiver surface which corresponds to the field-of-view angle of the pyrheliometer.

NOTE 6—All pyrheliometers listed in Refs (**1, 13, 14**) possess slope angles of approximately 1° and field-of-views between 5 and 6°.

NOTE 7—A fixed "shade slope angle" corresponding to the slope angle of the pyrheliometer can be stated only for pyranometers which are operated in a position normal to the sun. For pyranometers calibrated at fixed position, regardless of tilt, the shade slope angle varies according to the angle of incidence of the ray on the receiver plane.

7.8.1.4 Those parts of the disk mounting rod that obscure the field-of-view angle of the pyranometer should be as small as possible in order to restrict the disturbance of the signal to less than a total of 0.5 % when taking into consideration both the mount and any restrictions from neighboring instruments.

7.8.1.5 The shade disk must be easily removed and replaced in terms of shading and unshading of the pyranometers hemispherical glass dome such that the time spent in shading and unshading requires less than 5 % of the phase duration.

7.8.2 A number of types of shading disk devices are described in Appendix X5, several of which are commercially available.

8. Shaded-Unshaded Timing Sequence

8.1 Different methods of timing the shade and unshaded portions of the calibration sequence may be used. The most widely used sequence is to employ equal, or nearly equal, intervals for the both the shade and unshaded, or illumination, segments. Typical are 5 min shade and 5 min illumination, and 6 min shade and 6 min illumination.

8.2 An alternate method consists of using non-equal timing for the shaded and illuminated segments of the cycle in order to lessen the inaccuracies due to an approximately 1 % error introduced by the inclusion of the pyranometer-body thermal time constant to the time constant of the instruments thermopile. Typically, this consists of shading for approximately 30 thermopile time constants followed by illumination for a longer period of time such as 100 to 300 thermopile time constants. See Refs (**14, 15**) and Appendix X4 for discussions on time constant based timing.

9. Preparatory Steps

9.1 *Conditioning:*

9.1.1 Start the preparatory phase at least 30 min before the measurement phase is to begin. Allow for sufficient additional time to determine the pyranometer's thermopile time constant if it is not known.

9.1.2 Acclimatize the radiometers, electronics and data acquisition system by exposing the radiometers to the sun. Absolute cavity pyrheliometers should remain shuttered until the measurement sequence begins.

9.1.3 Turn on all electronics for a short warm-up period. Shade all electronics from direct sunlight.

9.1.4 Adjust all radiometers requiring alignment or leveling, the solar tracker(s) and the shading disk apparatus.

9.1.5 Perform electrical continuity and voltage checks, and perform any zeroing tests that may be required.

9.1.6 Clean all pyranometer domes and pyrheliometer windows.

9.2 *Determination of the Pyranometer's Thermopile Time Constant:*

9.2.1 Illuminate the field (test) pyranometer to be calibrated for 10 min (unshaded) and record the signal V_u. Then shade the pyranometer dome only for 60 s and record the signal V_s. Again illuminate (unshaded) the pyranometer and, taking continuous (not less than every 5 s if not analog) voltage readings, determine the time required for the response signal to reach 95 % of the final steady state value V_u. Record the time, t_c, as the instrument's thermopile time constant.

10. Procedure for the Alternating Shade Method

NOTE 8—Equations 2 and 3 in this method include interpolation of the shaded (diffuse) measurement voltages over two cycles of shading. This requires the assumption that the diffuse and direct beam irradiance are both smoothly and linearly changing over the period between the two shadings. A more direct, instantaneous, quantitative value for the shaded voltage can be obtained by using the ratio of the voltage signal of the unit under test to the signal of a continuously shaded pyranometer. See Appendix X3 and Appendix X4.

10.1 *Mounting:*

10.1.1 Mount the self-calibrating absolute cavity pyrheliometer (hereinafter designated the primary reference radiometer), or a secondary reference pyrheliometer (if a Type II calibration is desired) on either an altazimuth or equatorial sun tracker. If an equatorial tracker is used, set the latitude

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[6] A source of supply for the solar tracker is Kipp and Zonen, Delft, Holland, (Model 2AP). If you are aware of alternate suppliers, please provide this information to ASTM Headquarters. Your comments will receive careful consideration at a meeting at the responsible technical committee, which you may attend.

angle adjustment of the tracker to the exact local latitude. Align the reference pyrheliometer with the sight mechanism provided.

10.1.2 For calibration of the field pyranometer with axis vertical, mount the field (test) and any monitoring pyranometers used on a horizontal plate. Rotate each until the instrument cable connector faces the equator and level all instruments with the leveling screws and bubble levels provided.

NOTE 9—Mounting the body of a radiometer flush with a mounting plate will induce unwanted thermal transients that will affect the calibration of radiometers with thermal sensors and is not permitted.

10.1.3 For calibrations of field pyranometers either at normal incidence (that is, on a sun-tracking platform) or at a fixed, equator-facing tilt β from the horizontal, first precisely level the instruments on an exactly horizontal platform using the same technique as in 10.1.2. After leveling, mount the pyranometers either on a tilt table that is precisely adjusted to the required tilt from the horizontal, or on an altazimuth follow-the-sun mount for normal incidence calibrations.

10.1.4 While the instruments leveling procedure can compensate for somewhat non-level platforms when calibrating pyranometers with axis vertical, it is essential that the horizontal platform used to perform the initial instrument leveling on an exactly level, horizontal platform for instruments being calibrated at tilts from the horizontal.

10.2 *Equal Shade/Unshaded Time Intervals:*

10.2.1 Take $2n + 1$ voltage readings for each series of a set of s series of measurements performed over not less than two days, depending on sky conditions and the degree of scatter in the measurements observed within each series. The value s should not be less than six for clear sky conditions with little cirrus formation, to ten for haze and cirrus conditions. The essential requirement is that a sufficient number of series be obtained during which the mean solar incidence angles deviate less and ±5° from the mean angle representing the normal operating conditions of the pyranometer being calibrated.

10.2.2 Take each series of measurements in accordance with the timing sequence presented in Fig. 1, consisting of $n + 1$ shade intervals, during which the sensor is exposed to diffuse radiation only, alternating with n intervals during which the pyranometer is unshaded and exposed to hemispherical solar radiation.

10.2.3 The value of the time interval t_o should be from 20 to 60 response time constants determined in 9.2.1 and should be, typically, 2 to 5 min for WMO High Quality or ISO First Class pyranometers. The setting of the same time interval for the shading and illuminated sequences is based on the assumption that the response times of the pyranometer's thermopile during increasing and decreasing signals, that is, during shading and illumination, are approximately the same.

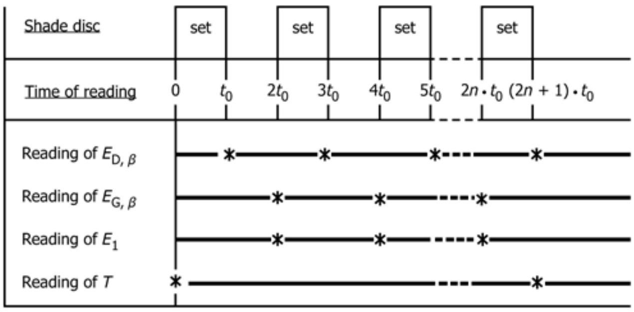


FIG. 1 Measurement Sequence for the Alternating Sun-and-Shade Method Using Equal Timing Intervals

10.2.4 Record the following values in accordance with Fig. 1: diffuse solar radiation signal $V_{D,\beta}$ measured with the shaded pyranometer for $n + 1$ intervals, including reflected solar irradiance if $\beta \neq 1$ (read and record at the end of each odd numbered shading interval nt_o); hemispherical solar radiation signal $V_{G,\beta}$ measured at the end of each even numbered exposed (illuminated) interval nt_o for n intervals; direct solar radiation signal V_I measured at each nt_o interval for $2n + 1$ measurements; and a measurement of the ambient air temperature, or pyranometer and pyrheliometer case temperatures, T, measured at least at the beginning and end of each series.

10.2.5 Record the time of each measurement required in 10.2.4 precisely in order to accurately calculate the solar incidence angles (see 12.1 – 12.4).

10.2.6 Restrict the number of intervals n such that the total duration of the series s is no more than 36 min (in order to ensure that the mean value of each series is associated with a small range of solar elevation and temperature.

10.2.7 For a pyranometer with a black and white detector, or any source of azimuthal asymmetry, steps 10.2.1 to 10.2.6 should be repeated after the radiometer has been rotated 60 degrees in azimuth. Record the azimuthal rotation angle with the signal data. Repeat the sequence until the radiometer returns to the original azimuth (6 rotations). See Appendix X4.

10.3 *Determination of the Calibration Factor:*

10.3.1 Determine the responsivity $R_S(i)$ and the mean responsivity $\bar{R}_S$, expressed as microvolts per watt per square meter (μV.watt^{-2}.m^{-2}) for each measurement and for the series, respectively, in accordance with:

$$R_s(i) = \frac{\{V_{G,\beta}(2i) - 0.5[V_{D,\beta}(2i-1) + V_{D,\beta}(2i+1)]\}}{\{V_I(2i)F_P\cos[\eta(2i)]\}} \tag{2}$$

and:

$$\bar{R}_S(S) = \frac{\sum_{i=1}^{n} R_{S(i)}}{n} \tag{3}$$

where:

or $V_{D,\beta}(2i + 1)$

i = indicates the measurement within the series,

S = indicates the series,

$V_{G,\beta}(2i)$ = the hemispherical solar irradiance signal measured at position $2i$ within the series, in millivolts, for example;

$V_{D,\beta}(2i-1)$ or $V_{D,\beta}(2i+1)$ = the diffuse solar irradiance signal for the shaded interval measured at position $(2i-1)$ or $(2i+1)$ within the series, in millivolts, for example;

$V_I(2i)F_P$ = the direct solar irradiance calculated from the product of the pyrheliometer signal and its calibration factor F_P;

$\eta(2i)$ = the angle between the direction of the solar beam and the perpendicular to the plane of the pyranometer's receiver at the time corresponding to position $2i$. The angle of incidence η is calculated from the equations given in 12.1 and 12.2 taking into account the inclined position of the pyranometer β and the solar position. The expression $\cos[\eta(2i)]$ in Eq 2 and 3 is unity for normal incident calibrations using a sun-following tracker to maintain the pyranometer's axis pointing to the sun.

n = the number of readings of $E_{G,\beta}$ and E_I to be used from the total number of reading intervals ($2n + 1$).

10.3.2 For a pyranometer with a black-and-white detector, perform the computations in 10.3.1 for each of 6 incremental 60° azimuthal rotation positions.

10.3.3 Identify and reject those $R_S(i)$ which deviate by more than 1 % from $\bar{R}_S$. If more than $n/2$ are rejected, eliminate the series from further calculations.

NOTE 10—The ±1 % deviation limit specified in 10.3.2 will result in R_s values for restricted ranges of zenith/incidence angles, and not all zenith/incidence angles, since all pyranometers eventually deviate by more than ±1 % from a mean value at some zenith/incident angles as zenith/incidence angles increase.

10.3.4 If there are sufficient $R_S(i)$, calculate a corrected value R_S:

$$R_S = \bar{R}_S(i, i = 1, n \text{ for } i \neq j) \tag{4}$$

where: j are those measurements i which were identified as deviating by 1 % from $\bar{R}_s$.

10.3.5 If ρ calibration series are carried out at the desired parameter ranges, the final responsivity is R is calculated as the mean of all responsivities *RS:*

$$R = \frac{1}{\rho}\sum_{s=1}^{\rho} R_S(S) \tag{5}$$

NOTE 11—Because the cosine response of the pyranometer is not flat, the computation of unweighted mean responsivities for a pyranometer over a range parameters, specifically a set of zenith/incidence angles, does not represent the responsivity of a lambertian (perfect cosine response) detector in the presence of normally distributed random errors. Measurements of solar radiation at an arbitrary zenith/incidence angle, η_a, derived using the mean R_s will be in error with respect to measurements accomplished with the correct responsivity at the given incidence/zenith, angle η $R_s(\eta)$. The magnitude of the error is a function of the cosine response of the individual instrument. For a pyranometer with a black and white detector, the same argument applies to the azimuthal dependence as well (**13, 14**).

If a reduction formula $f(T,T_n)$ is available and there are some series in which the temperature deviates significantly from the desired value T_n, then apply the correction factor to each R_S according to:

$$R = \frac{1}{\rho}\sum_{S=1}^{\rho} f[T(S),T_n]R_s(S) \tag{6}$$

NOTE 12—For some types of pyranometers, temperature coefficients α are specified such that the correction factor is simply $f(T, T_n) = [1 - \alpha(T - T_n)]$.

10.3.6 Present the final result also in the form of a calibration factor F, expressed in watts per square metres per microvolt:

$$F = \frac{1}{R} \tag{7}$$

and the responsivity R.

NOTE 13—Note 11 in 10.3.5 applies to the derived calibration factor as a function of η, the incidence/zenith angle, as well as to the responsivity.

11. Procedure for the Continuous Sun-and-Shade (Component Summation) Method

11.1 *Mounting:*

11.1.1 Mount the reference pyrheliometer as prescribed in 10.1.1.

11.1.2 Mount the reference pyranometer, which has been previously calibrated by the alternating shade method (10.2 or 10.3) on the appropriate platform depending on the tilt from the horizontal chose (0° to β) selected for the calibrations, or on the appropriate tracker for normal incidence calibrations.

NOTE 14—For the best absolute accuracy, the reference pyranometer should have the lowest thermal offset possible. Presently, only pyranometers with black and white detectors, or all-black pyranometers with compensating thermopiles connected in opposition to the active detectors are known to meet this requirement. The method of Appendix X3 for calibrating the black-and-white reference pyranometer will produce the lowest uncertainty in the reference irradiance (**14**).

11.1.3 Affix the shade disk over the reference pyranometer, and ensure that it will remain rigid and optically aligned throughout the entire calibration procedure. Use of an automatic, sun-tracking shade disk is recommended, although a manually adjusting disk can be used albeit with considerable difficulty.

11.1.4 Mount the test (field) pyranometer(s) being calibrated on the appropriate platform(s) or on an altazimuth sun tracking platform such that the plane of all of the test pyranometers' receivers are precisely aligned with the plane of the receiver of the continuously shaded reference pyranometer.

NOTE 15—As noted previously one of the advantages of this method is that any number of pyranometers of mixed type and classification may be calibrated at the same time, limited only by the facilities available for mounting the test (field) pyranometers to be calibrated.

11.2 *Data Acquisition and Recording:*

11.2.1 See section 7.2 on Apparatus.

11.2.2 Take between 10 and 12 series S of 10 to 20 sets of instantaneous readings over a minimum of a two-day period (three days are preferred). Ensure that each set consists of instantaneous readings taken approximately every 20 to 30 s for a duration of between 10 and 20 min. Voltages from the reference pyrheliometer, shaded reference pyranometer, and all test (field) pyranometers should be taken within 1 s of each other. Limit each series to reasonably stable atmospheric conditions. Ensure that the total number of series are taken over a minimum of a two-day period (over three days are preferred).

NOTE 16—If the pyrheliometer is capable of measuring direct solar irradiance continuously, the use of integrated values is possible. The integration interval should be no greater than 6 min or 2 min, depending on whether the sky is clear or hazy/cloudy, respectively. Non-negligible uncertainties may be introduced in the calculation of R_S by using the mean solar incidence angle η over the integration interval.

11.3 *Determination of the Calibration Factor:*

11.3.1 Eliminate from the calculation all sets which deviate from the corresponding series mean by more than 5 %. Discard any series if more than 50 % of the sets have been eliminated.

11.3.2 Calculate the mean responsivity R_S, expressed in microvolts per watt per square meter, from single reading of one measuring series:

$$R_S = \frac{\frac{1}{\rho}\sum_{i=1/i\neq j}^{k} V_{G,\beta}(i)}{\sum_{i=1/i\neq j}^{k}\left[V_I(i)F_\rho \cos\eta(i) + V_{D,\beta}(i)F_D\right]} \tag{8}$$

where the definitions for i is given in 10.3.1 and the definition of ρ is given in 10.3.5 and the notations for hemispherical solar irradiance signals $V_{G,B}$, diffuse solar irradiance, $V_{D,B}$, and direct normal solar irradiance V_I are the same except that the i^{th} replaces the $2i^{th}$ notation, and:

k = the total number of readings of each radiometric quantity, equal to the total number of data sets,

F_D = the diffuse irradiance calibration factor of the reference pyranometer, and

F_P = the calibration factor of the reference pyrheliometer.

11.4 Calculate the instrument calibration constants F and responsivities R of the test (field) pyranometer(s) in accordance with the procedures of 10.3, Eq 7.

12. Calculation of the Angle of Incidence η of Direct Radiation on Planar Surfaces

NOTE 17—The computation of the incidence angle presented here is a first approximation, and contains inherent errors with respect to an astronomically correct calculation of the position of the sun as produced using the Nautical Almanac algorithms. Typical uncertainty in the zenith/incidence angle for this calculation can approach 0.2° for zenith angles of the sun less than 75°, and up to 0.5° for zenith angles greater than 75°, because no correction for refraction effects in the atmosphere are included. Detailed, more accurate solar position, and hence zenith angle computation algorithms can be found in Michalsky (**16, 17**) (uncertainty ±0.1°) and Reda and Andreas (**18**) (uncertainty ±0.003°).

12.1 *Computation of the Hour Angle:*

12.1.1 First compute the hour angle ω from solar noon with solar noon being zero (angle between the hour circle of the sun and the local meridian, at the precise time of the measurement).

NOTE 18—Computing ½ of the interval from sunrise to sunset in (decimal) hours, and adding to the sunrise time (all in decimal, hh.hh) results in solar noon. Many Internet sites are available for either computing sunrise/set times, or times of solar noon (for example, The U.S. Naval Observatory at http://aa.usno.navy.mil/data/).

12.1.2 Each hour represents 15° of longitude with mornings negative and afternoons positive. For example, ω = –15° for 11:00 a.m. and ω = +37.5° for 4:30 p.m.

12.2 *Computation of the Solar Declination δ*

12.2.1 Next, compute the solar declination in accordance with:

$$\delta = 23.45\sin\left[0.9863(d + 283.4)\right] \tag{9}$$

where: d is the sequential day number of the day of the year (Jan 1 =1, Dec 31=365 for non-leap years).

12.3 *Computation of the Solar Elevation and Solar Azimuth Angles:*

12.3.1 Using the declination angle δ from Eq 9, compute the solar elevation associated with each measurement in accordance with:

$$\sin\gamma = (\sin\varphi \cdot \sin\delta) + (\cos\varphi \cdot \cos\delta \cdot \cos\omega) \tag{10}$$

where:

φ = the geographical latitude of the calibration site,

δ = the solar declination from Eq 9, and

ω = the solar hour angle computed in 12.1.2.

12.3.2 Next, taking the value for solar elevation angle determined using Eq 10, compute the solar azimuth angle ψ in accordance with:

$$\cos\psi = \frac{(\sin\varphi \cdot \sin\gamma) - \sin\delta}{\cos\varphi \cdot \cos\gamma} \tag{11}$$

where: ψ is measured from the south, being positive to the west and negative to the east.

12.4 *Computation of the Angle of Incidence of the Direct (Beam) Component:*

12.4.1 Compute the angle of incidence of the direct (beam) component of solar radiation using the following equation:

$$\cos\eta = (\sin\gamma \cdot \cos\beta) + [\cos\gamma \cdot \sin\beta \cdot \cos(\alpha - \psi)] \tag{12}$$

where:

α = the azimuth angle of the vertical plane normal to the plane of the pyranometer's receiver.

12.4.2 The reader is referred to the diagram in Appendix X3 for greater details pertaining to the definition of the angle of incidence η between the direction of the sun and the normal to the tilted plane (the plane of the pyranometer's receiver).

13. The Certificate of Calibration

13.1 The certificate shall state as a minimum the following information:

13.1.1 *The Test Pyranometer:*

13.1.1.1 Manufacturer, type and serial number,

13.1.1.2 Inclination angle (tilt), azimuthal orientation, tracking (normal incidence),

13.1.1.3 Special remarks on state of instrument,

13.2 *The Reference Instrument(s):*

13.2.1 Manufacturer(s), type(s) and serial number(s),

13.2.2 Hierarchy of traceability,

13.2.3 Shade disk geometry and other pertinent details, and

13.2.4 Corrections applied.

13.3 *The Procedure:*

13.3.1 Reference to this standard (and to ISO 9846, if appropriate),

13.3.2 Type of procedure (including shade/unshaded timing sequence as appropriate),

13.3.3 Date and time of calibration,

13.3.4 Number of series,

13.3.5 Ranges of measurement parameters (solar elevation angle, hemispherical solar irradiance, ratio of direct to global irradiance, turbidity (when determined), temperature, and

13.3.6 Application of reduction formulae.

13.4 *Results of Calibration:*

13.4.1 Responsivity, expressed in microvolts per watt per square metre,

13.4.2 Final mean value of R,

13.4.3 Calibration factor, expressed in watt square meters per microvolt,

13.4.4 Standard deviation of R_S related to R, and

13.4.5 Statement of the estimated uncertainty in the calibration value, and a brief description of how the estimate was obtained.

14. Precision and Bias

14.1 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 conditions This is the transfer precision.

14.1.1 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 pyreheliometer.

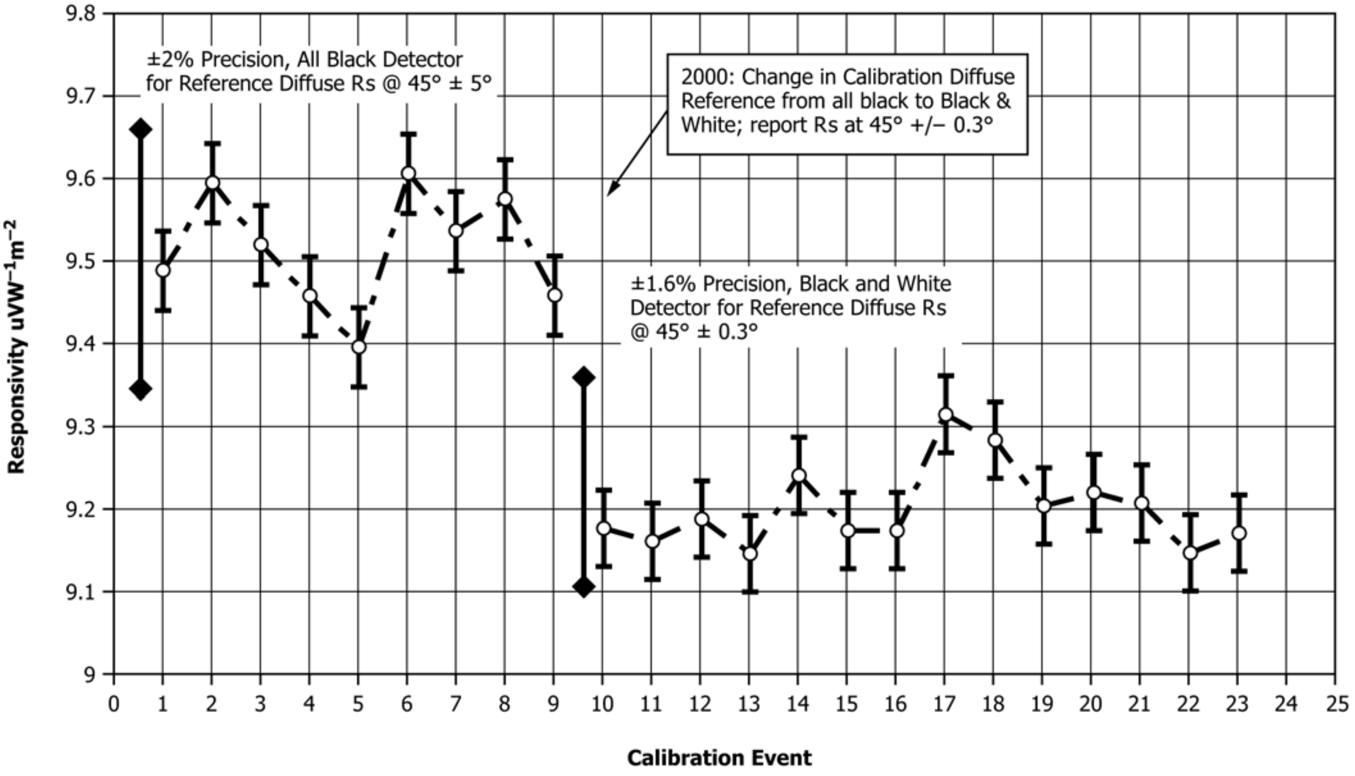
14.1.2 Data for repeated calibrations of pyrheliometers with respect to a primary reference pyrheliometer show within laboratory precision less than 2.5 %, and less than 1.8 % is achievable, if a specified, limited zenith angle range is specified. (See Fig. 2 and Table 2.)

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

	WRR Factors (Ratio to WRR = 1)		Percent Difference
	IPC–IX	Local IPC	
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

14.1.3 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.)

NOTE 19—Transfer of WRR to a reference absolute cavity radiometer can be achieved through direct comparison to the WRR at an International IPC (as in 2nd column above) or by transfer from a (several) reference cavity radiometer(s) carrying a WRR factor in a LOCAL (sometimes called a REGIONAL) intercomparison, as in the third column above. In the example, IPC-IX represents one laboratory, and the Local IPC represents a second, independent laboratory; and the same intercomparison protocol is conducted at each.



NOTE 1—Before 2000, reference diffuse radiometer for component summation technique was all-black detector pyranometer, R_s reported as mean of R_s in zenith angle range from 40 to 50°, that is, 45 ± 5°. As of 2000, reference diffuse radiometer a black and white detector radiometer, and R_s reported for zenith angle range of ±1° centered at z = 45°. Data available at http://www.nrel.gov/aim (Calibration Histories)

FIG. 2 Typical Within Laboratory Precision for Pyranometer Calibrations

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

	Units = μV W^{-1} m^{-2}		Between	Within	Within[A]
	Lab A R_s	Lab B R_s	Lab A–Lab B %	Lab A %	Lab B %
			Between Laboratory Bias	Within Laboratory Precision	
Event (Instrument #1)					
1	8.627				
2	8.627			0.00	
3		8.665	0.44		
4	8.574		1.06	0.61	
5		8.646	0.84		0.22
B	8.547		1.16	0.31	
Note: Cal Ref Change Event					
7		8.384	1.91		(3.03)[A]
8		8.353			0.37
9	8.271				
10		8.382	1.34		
11		8.401			0.22
12	8.198		2.41	0.88	
13		8.297	1.20		1.24
14	8.237		0.72	0.72	
15	8.396				
16	8.360			0.43	
17		8.438	0.93		
18		8.318			1.42
19	8.223			3.88	
Instrument #2					
20		8.362	1.69		
21		8.428			0.79
Note: Calib. Ref Change Event					
22		(8.164)[A]			
23		8.171			0.00
24		8.135			0.44
25		8.182			0.58
26		8.110			0.88
27	7.969				
28		8.047	0.98		
		Coefficient of Variation (%)	1.25	0.98	

[A] Excluded from analysis due to shift in calibration reference.

14.1.4 Published reports of uncertainty analysis for field pyranometer calibrations show the transfer precision of pyrheliometer calibration values within a laboratory are on the order of 0.5 % for an individual calibration value within a period of 10 minutes (**13**).

14.1.5 Data for repeated calibrations of pyranometers with respect to a primary reference pyrheliometer show between laboratory precision of less than (but approaching) 2.0 %. (See Table 2.)

14.2 Bias in the derived calibration factor of the field or secondary standard pyranometer 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.

14.2.1 Within laboratory bias estimates will vary with data logging equipment performance, environmental conditions (such as aerosol optical depth and consequent circumsolar radiation, wind, ambient temperature) and range of zenith angles used to compute the result.

14.2.2 Published reports of uncertainty analysis for field pyranometer calibrations show the estimated bias from one calibration to another (between laboratories) for pyranometer calibration values are on the order of 2.5 % for an individual calibration value.

14.2.3 For the data in Table 2, Laboratory A and Laboratory B exchanged two instruments (#1 and #2) periodically over a nine year period (1996–2004) and reported the indicated calibration values. Column 1 is the calibration event number. Column 2 is the reported calibration value (Responsivity, R_s, μV/W/m^{-2}) from laboratory A. Column 3 is the reported calibration value (R_s) from laboratory B. Column 4 is the absolute value of the percent difference between adjacent calibration R_s values expressed as a percent of the earliest R_s value in the pair. Columns 5 and 6 are the absolute value of the percent difference between adjacent calibration R_s values within a laboratory expressed as a percent of the earliest R_s value in the pair At the bottom of column 4 is the average difference (bias) between laboratories in percent. At the bottom of columns 5 and 6 is the coefficient of variation between adjacent calibrations within each laboratory expressed in percent. All sample sizes in the calibration events were greater than 1000.

NOTE 20—Table 2 includes a change in calibration diffuse reference and reporting technique at event 7 (same change occurred for event 22). Thus there are reports for before and after the calibration change. The results from the two periods are treated as independent results. Data in Table 2 and Fig. 2 are a compilation of 23 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.

14.3 A basic uncertainty in the determination of the calibration factor is inherent in the use of the reference pyrheliometer. This uncertainty arising initially by the transfer of SI units to the pyrheliometer, amounts to about 0.4 %, 0.7 %, and 1.0 % for a self-calibrating absolute cavity pyrheliometer, ISO Secondary Standard pyrheliometer and ISO First Class pyrheliometer, respectively. These values are increased to 0.9 % and 1.5 % for the ISO Secondary Standard and ISO First Class pyrheliometers, respectively, because of the permissible range of instrument instability over two years (see ISO 9060).

NOTE 21—In the case of the continuous sun-and-shade (component summation) method, a well-characterized pyranometer with a small or negligible zero offset contributes to the uncertainty of the reference values of the hemispherical solar irradiance by less than 1 % if the sky is cloudless.

14.3.1 The level of uncertainty resulting from carrying out the calibration procedure can be reduced to less than 1 % by accurate adjustments, operational factors for the shade disk geometry, and careful operation. (See Table 2.)

NOTE 22—Since the uncertainty in determining the pyranometer inclination is at least 0.1°, the calibration uncertainty increases with the angle of incidence because of the factor cos η. Therefore a 1 % uncertainty requires that the angles of incidence are restricted to less than 60°.

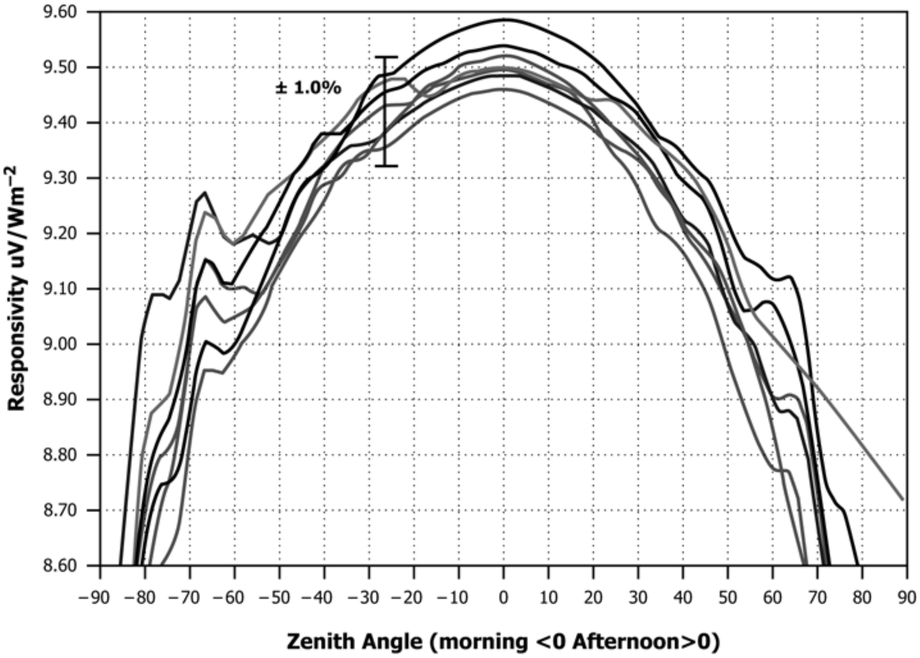
14.4 The sample standard deviation, variance, or coefficient of variation calculated from the results of all series, is indicative of the variation in meteorological conditions (wind, cirrus), and instrument characteristics (cosine and azimuth response). The level of these uncertainties will depend on the tolerated ranges of the test parameters.

14.5 Fundamental differences between the alternating and the continuous sun-and-shade (component summation) methods do not exist, depending on the magnitude of the thermal zero offset in the reference pyranometer for the reference diffuse in the component summation method, which usually is unknown. The first method should be applied, using a diffuse reference pyranometer with a low thermal offset, when scattered cloud conditions are typical. The calibration factors determined with the latter method, supported by careful zeroing procedures and careful installation of the test and reference pyranometers such that they "see" exactly the same horizon and foreground, are preferred for clear sky conditions. The calibration factor of the latter method may be higher by about 0.5 %. A detailed comparison of the two methods is given in Appendix X6.

15. Measurement Uncertainty

15.1 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 14, which were derived from an interlaboratory study.

15.2 It is neither appropriate for, nor the responsibility of this test method to provide explicit values that a user of the



NOTE 1—The error bar is derived from the range of responsivity over the reported zenith angle range (30 to 60°), for a series of eight calibrations, with respect to a responsivity at 45 ± 1°. The uncertainty in a pyranometer measurement will depend on the zenith/incidence angle at the time of measurement. A functional approximation to the responsivity as a function of zenith angle can reduce the bias errors to some degree, but the functional fit is not necessarily representative of all geometry and environmental conditions (which may differ from those during the calibration).

FIG. 3 Example for Pyranometer Uncertainty Estimate

method would quote as their estimate of uncertainty. Uncertainty values must be based on data generated by a laboratory reporting results using the method.

15.3 Measurement uncertainties should be evaluated and expressed according to the U.S. version of the ISO Guide to Estimating the Uncertainty in Measurements (**19**) published by the American National Standards Institute (ANSI). Condensed summaries of the principles described in the ISO guide are available from the National Institute of Standards and Technology (**20**), United Kingdom Accreditation Service (**21**), and Singapore Accreditation Council-Singapore Laboratory Accreditation Scheme (SAC-SINGLAS) (**22**).

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

15.5 Uncertainty in calibration results obtained using this method depends on the calibration uncertainties for the instrumentation used, pyranometer characteristics (detector offsets, cosine response), and the signal noise encountered during the calibrations.

15.6 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, standard deviation, or coefficient of variation.

15.7 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. (See 13.4.5 and Fig. 3.)

15.8 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 arrived at. (See 13.4.5 and Fig. 3.)

15.9 Fig. 3 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 +2 % to –5 % expanded uncertainty derived in the example must be combined with the expanded uncertainty arising from the reference pyrheliometer, data logger, and environmental conditions.

APPENDIXES

(Nonmandatory Information)

X1. SHADE DISC DEVICES

X1.1 A shade disc device for screening the direct solar radiation to measure the diffuse solar radiation by a pyranometer consists of:

X1.1.1 *A Disc:*

X1.1.1.1 Of a well-defined radius *r* [≥ radius of pyranometer dome + *d* tan 0.5°; for *d*, see X1.1.2];

X1.1.1.2 Painted black on the side opposite to the pyranometer; and

X1.1.1.3 Equipped with a means to fasten the disc to the support.

X1.1.2 *A Disc Support, designed to:*

X1.1.2.1 Be as small as possible (to minimize additional shading of the pyranometer);

X1.1.2.2 Be as rigid as possible (to avoid large disc movement caused by wind);

X1.1.2.3 Allow movement of the disc for screening the sun; and

X1.1.2.4 Fix the distance d between the disc centre and the centre of the receiver for any position of the disc.

X1.1.3 *A Mount, Designed to:*

X1.1.3.1 Bear the disc support;

X1.1.3.2 Move the support, manually or by a motor, in order to keep the disc in the correct shading position; and

X1.1.3.3 Be fastened to the instrument platform or similar.

X1.1.4 The so-called shading-angle α_s = 2 arctan (*r/d*) should be approximately equal to the field-of-view angle of the pyrheliometer used for calibration.

X1.1.5 During measurements, the distance *d* should be kept constant and independent of the position of the sun.

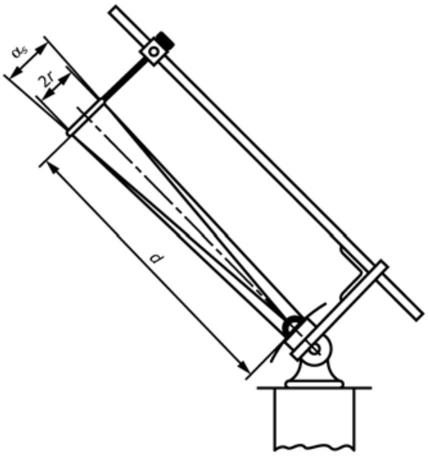
X1.1.6 The disc should be positioned perpendicularly to the sun's ray and shall screen the receiver surface and the glass domes on circular-symmetrical surfaces at normal incidence.

X1.2 Some types of sun-shading devices are briefly described below.

X1.2.1 *Shade Disc Device of a Sun-Tracking Pyranometer (Operated at Normal Incidence):*

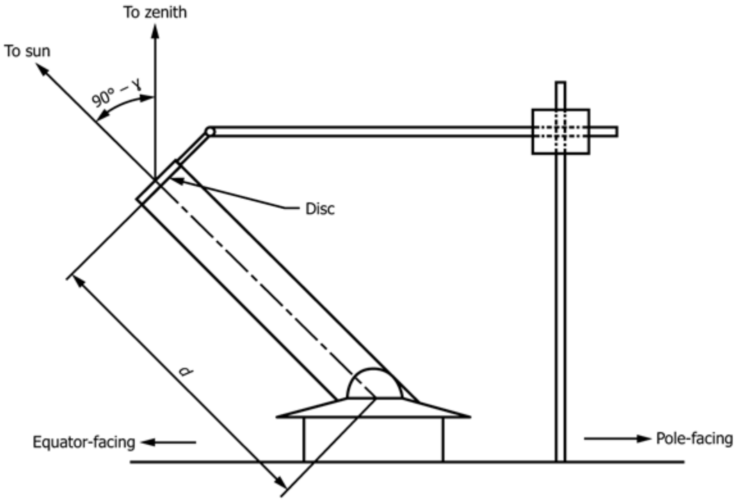
X1.2.1.1 As shown in Fig. X1.1, the mount of the shading device is fixed to a moving pyranometer platform. The disc can be shifted along the rod and may be removed.

X1.2.2 *Manually Operated Shade Disc Device for Stationary Pyranometers:*



α_s = 2 arctan r/d

FIG. X1.1 Shade Disc Device Used with a Sun-Tracking Pyranometer



γ: Solar elevation angle

FIG. X1.2 Shade Disc Device Installed Alongside the Pyranometer

X1.2.2.1 *Mount Alongside the Pyranometer*—As shown in Fig. X1.2, the mount is designed as a turnable rod standing upright on the polar side of the pyranometer. The rod supporting the disc is rotated horizontally to set the disc. (It is not feasible to set the disc at a constant distance to the receiver.)

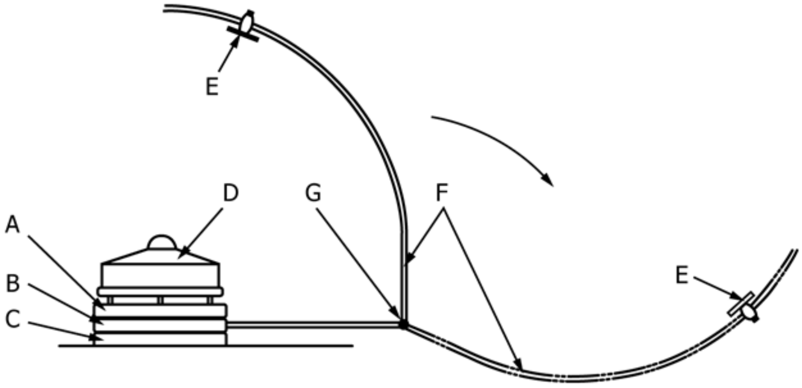
X1.2.2.2 *Mount Concentric to the Pyranometer*—As shown in Fig. X1.3, a plate-sized turnable mount allows adjustment of the azimuth position of the disc. To follow the solar elevation, the disc is shifted along the circularly curved rod. For rapid setting of the disc, the rod can be tilted up or down.

X1.2.3 *Semi-automatic Motor-Driven Device for Continuous Shading*—As shown in Fig. X1.4, the mount of the shade disc is driven synchronously with the solar hour angle. The hour angle axis is directed to the elevated pole (parallactic operation). To follow the solar declination, the disc must be shifted manually. The receiver of the fixed pyranometer is always at the same distance from the disc because of the appropriate dimensions of the rod. The compact design allows for continuous operation and requires minimum space.

X1.2.4 *Fully Automatic Motor-Driven Device for Continuous or Alternating Shading:*

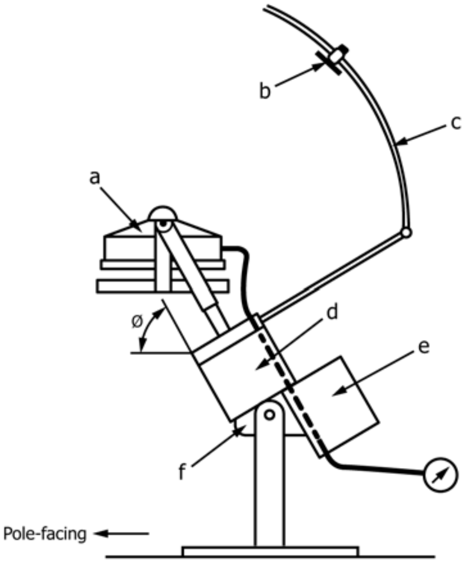
X1.2.4.1 A computer-controlled solar tracker with fully automatic movement of a shade disc is commercially available. The pyranometer is mounted on a box within which the motor rotates the rod with the shade disc according to the solar elevation. The motor housing is mounted on a pillar which is driven by a second motor and moves the shade disc in the case of a horizontally-levelled pyranometer (see Fig. X1.5 illustrating a solar tracker) according to the sun's azimuth. If the pyranometer has to be calibrated in a tilted position, the tracker device can be operated in tilted mode (see Fig. X1.5). Because of the computer control of the disc movement, the removal and the setting of the disc during the calibration process is easily programmable.

X1.2.4.2 This device does not completely fulfill the requirements in Fig. X1.5, since the distance *c* between the receiver plane and the elevation axis is not zero.



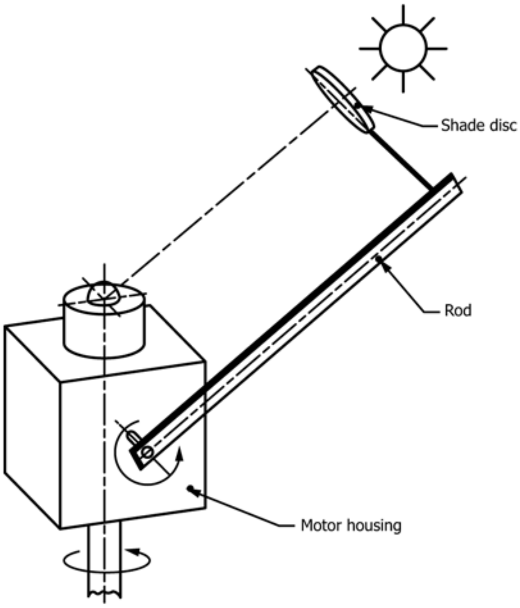
A: Rotatable plate for turning the pyranometer D separately
B: Rotatable plate bearing the circularly curved rod F of the shade disc E
C: Fixed mount
G: Joint to tilt the shade rod up or down

FIG. X1.3 Shade Disc Device, Installed Concentrically to the Pyranometer (System MetObs Hamburg)

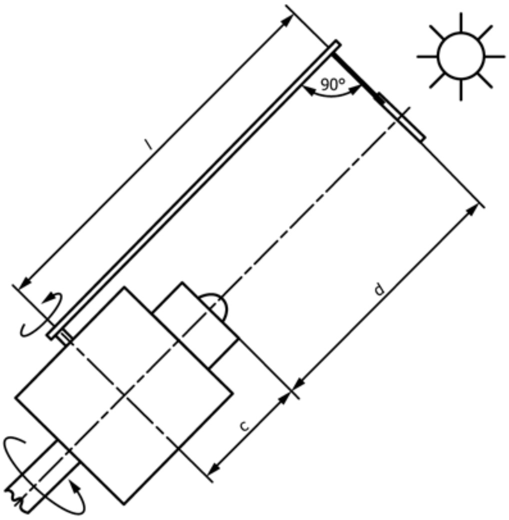


a: Pyranometer
b: Shade disc
c: Circularly curved rod for manual shifting of the shade disc
d: Gear
e: Synchronous motor
f: Joint for tilting the axis which points the rod to the elevated pole

FIG. X1.4 Semi-Automatic Shade Disc Device



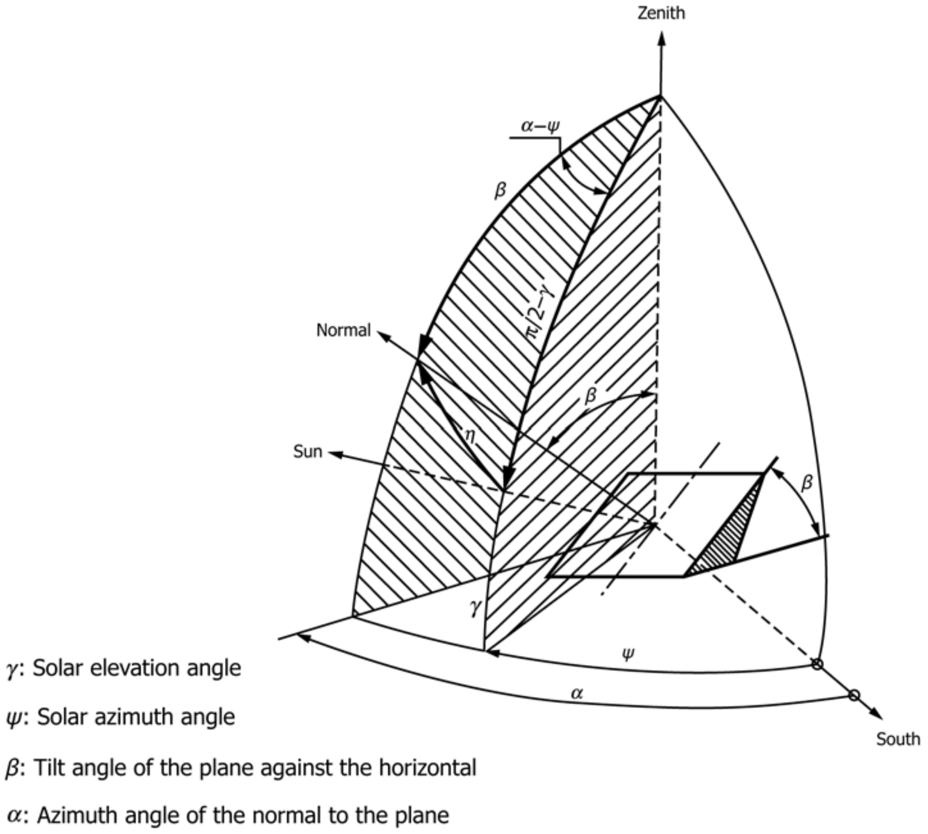
a) Solar tracker with shade disc



b) Solar tracker in tilted position

FIG. X1.5 Fully Automatic Shade Disc Tracker

X2. SCHEMATIC OF THE ANGLES RELATING TO THE INCIDENCE ANGLE OF THE DIRECT BEAM



γ: Solar elevation angle
ψ: Solar azimuth angle
β: Tilt angle of the plane against the horizontal
α: Azimuth angle of the normal to the plane

FIG. X2.1 Schematic of the Angles Relating to the Incidence Angle of the Direct Beam

X3. EXTENDED VERSION OF THE SUN-AND-SHADE METHOD

X3.1 A modification to the sun-and-shade method allows accurate determination of the diffuse solar irradiance signal during the exposed phase, even when the sky conditions are less stable (for instance, varying atmospheric turbidity or cloudiness).

X3.1.1 This test method additionally requires a continuously-shaded pyranometer which is operated using the same orientation and the same shade geometry as the test pyranometer.

X3.2 $V_{D,\beta}(2i)$ (see 10.3.1) is obtained more accurately by reference to the signal from a continuously-shaded pyranometer $V_{D,\beta}$:

$$V_{D,\beta}(2i) = \frac{k_1 + k_2}{2} \cdot V_{D,\beta}{}^{\circ}(2i) \qquad \text{(X3.1)}$$

where:

k_1 = $V_{D,\beta}(2i - 1)/V_{D,\beta}{}^{\circ}(2i - 1)$
k_2 = $V_{D,\beta}(2i + 1)/V_{D,\beta}{}^{\circ}(2i + 1)$

k_1 and k_2 readings should take place during a minimum of about 10 min.

X3.2.1 $V_{D,\beta}(2i)$ replaces the interpolation term $0{,}5[V_{D,\beta}(2i - 1) + V_{D,\beta}(2i + 1)]$ in the responsivity Eq 2 and 3 (see 10.3.1).

X3.3 This test method is presently used and recommended by the Canadian Atmospheric Environment Service (AES).

X4. ALTERNATING SUN-AND-SHADE METHOD WITH AZIMUTH RESPONSE AVERAGING

X4.1 This method produces an average responsivity suitable for measuring diffuse reference irradiance with pyranometers that have black and white detectors. These radiometers produce the most accurate reference diffuse measurement for the component summation technique, because of the small (less than 2 Wm^{-2}) thermal offsets in the instruments. The pattern of the black and white detector absorber paint results in significant azimuthal variation in the responsivity. This method was developed at the National Renewable Energy Laboratory, Golden, Colorado (see Refs **8, 9**).

X4.2 The technique requires a shaded control pyranometer, as in the Extended Version of the Sun-Shade Method described in Appendix X1, a reference pyrheliometer, and the unit(s) under test.

X4.3 Mount the test and control pyranometers and the reference pyrheliometer on sun trackers. The control and test radiometers are mounted with detectors horizontal. Mount the shading disk/ball mechanism with dimensions suitable for matching the field of view of the pyrheliometer.

X4.4 Calculate the average of the last three readings in each shade-unshade cycle, to allow for pyranometer settling time after each change of shade state.

X4.5 Repeat the shade-unshade sequence three times.

X4.6 Conduct the sequences so the data includes the zenith angle ranges from 40° to 50°, as the final R_s will represent the R_s at $\eta = 45°$.

X4.7 *Procedure*—Begin the first shade/unshade sequence by shading test and control radiometers for at least 30 time constants (150 s for an Eppley Model 8-48 pyranometer). The azimuth of the test radiometer is 0° (connector points North, to azimuth 360°).

X4.7.1 While the control pyranometer is continuously shaded, unshade the test pyranometer for 60 time constants (300 s for Eppley Model 8-48). Record the zenith angle, $\eta(\theta = 0)$, and signals $V_{Gt}(\theta = 0)$, $V_{Dc}(\theta = 0)$, and $V_B(\theta = 0)$.

where:

$\eta(\theta = 0)$ = zenith angle at azimuth $\theta = 0°$,
$V_{Gt}(\eta = 0)$ = signal of test unit, azimuth $\theta = 0°$,
$V_{Dc}(\eta = 0)$ = signal of shaded control unit, azimuth $\theta = 0°$, and
$V_B(\eta = 0)$ = signal of pyrheliometer, azimuth $\theta = 0°$.

X4.7.2 Every 60 s after the initial settling time, rotate the unshaded test radiometer 60° in azimuth, to 60°, 120°, 180°, 240°, and 300°. At each azimuth record η_i, $V_{Gt}(\theta j)$, $V_{Dc}(\theta\ j)$, and $V_B(\theta j)$; $j = 2$ to 6.

X4.7.3 End the unshade sequence by rotating the test radiometer back to azimuth $\theta = 0°$ and shading it for 30 time constants. At the end of the 30 time constant period, record the ratio of the shaded test and control radiometer signals: $k_1 = V_{Dt}(0)/V_{Dc}(0)$; where $V_{Dt}(0)$ is the signal from the shaded test unit, and the zenith angle η_1.

X4.7.4 End the sequence by unshading the test units for 30 time constants.

X4.7.5 Repeat the unshade-shade sequence of X4.7.1 to X4.7.4 two more times, to acquire three sets of shaded data (ith zenith angles), three sets of unshaded data (with rotations while unshaded an zenith angles), three ratios $K_i = V_{Dt}(0)_i/V_{Dc}(0)_i$, and the zenith angle at which the ratios were computed, η_i, for $i = 1$ to 3 (obtained at the beginning of each shaded period; see Fig. X4.1).

X4.7.6 Using linear regression, fit the data points (k_1, η_1), (k_2, η_2), (k_3, η_3) to the linear function $k(\eta) = a + b\eta$.

X4.7.7 For each of the three sets of unshaded data, from the known zenith angles at each unshaded rotation positions, ($j = 1$ to 6) calculate the shade ratio $k(\eta_j)$, as in X4.7.3 and compute the equivalent shaded voltage, V_{Dt}, of the test pyranometer as the product of the shaded control pyranometer voltage, V_{Dc}, and the shade ratio:

$$V_{Dt}(\eta_j) = k(\eta_j) \cdot V_{Dc}(\eta_j) \qquad \text{(X4.1)}$$

X4.7.8 For each of the three ($i = 1$ to 3) unshade sequences, and $j = 1$ to 6 responsivities at each rotation position, calculate the responsivity $R_s[\eta\ (i, j)]$:

$$R_s[\eta(i,j)] = \frac{[V_{Gt}(i,j) - V_{Dt}(i,j)]}{V_I(i,j) F_p \cos[\eta(i,j)]} \quad i = 1 \text{ to } 3;\ j = 1 \text{ to } 6 \qquad \text{(X4.2)}$$

where:

$V_{Gt}(i,j)$ = the test pyranometer unshaded signal in millivolts at the jth rotational position in the ith sequence,
$V_{Dt}(i,j)$ = the test pyranometer shaded signal in millivolts at the jth rotational position in the ith sequence from Eq X4.1 in X4.7.7,
$V_I(i,j)$ = the reference pyrheliometer signal in millivolts at the jth rotational position in the ith sequence,
F_p = the reference pyheliometer calibration factor (Wm^{-2}mv^{-1}), and
$\eta(i,j)$ = the zenith angle (incidence angle) in degrees at the jth rotational position in the ith sequence.

This will produce three responsivities versus zenith angle data sets for the three unshaded sequences.

X4.7.9 Using linear regression, for each of the six azimuthal rotation positions ($j = 1$ to 6) fit the three data points $R_s(\eta_i)[j]$ to the linear function $R_s(\eta)[j] = a + b\ \eta[j]$.

X4.7.10 From the six derived linear equations, compute the R_s at $\eta = 45°$.

X4.7.11 The average of the six derived R_s at $\eta = 45°$ is the diffuse responsivity of the test radiometer.

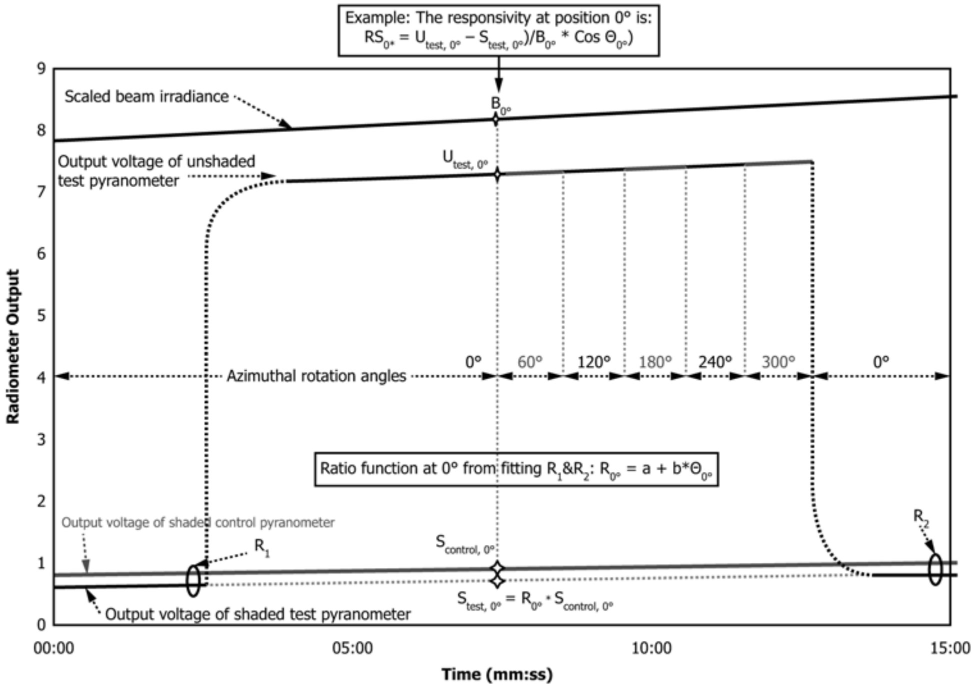


FIG. X4.1 Timing Sequence for Measurement of Shading Ratios, Unshade Signals at 60° Rotation Intervals, and Unshade/Shade Sequence

X5. MULTIPLE-READING VERSION OF THE ALTERNATING SUN-AND-SHADE METHOD

X5.1 The aim of this version is to reduce the effects of random scatter (by wind, dust, etc.) on the single values in a series by the averaging of ten values (instead of one) of the respective radiometers in the final phase of each phase, and using the mean of these readings in further calculations. The unbiased estimate of the standard deviations gives, as an additional advantage, a measure of the uncertainty of the readings.

X5.2 This version permits fully automatic operation of the radiometers and should be applied in fully automated calibration procedures. The use of a computer is necessary.

X5.3 The following modifications of 5.6.2 need to be considered for each radiometer channel.

X5.3.1 Systematically take ten readings within the last $0.15t_0$ s of each interval (the 10th reading corresponds to the single reading in the basic version, t_0 being the interval time).

X5.3.2 Calculate the arithmetic mean value of the ten readings.

X5.3.3 Compare the ten individual readings with the calculated mean value and reject those readings which deviate by more than 0.5 %. If more than 50 % of one radiometer channel's readings are rejected, then cancel the mean values of all channels.

X5.3.4 Calculate a new mean value using the remaining readings and the unbiased estimate of the standard deviation.

X5.3.5 Use this new mean value in the further calculations described in 5.6.3.

X6. COMPARISON OF THE ALTERNATING SUN-AND-SHADE METHOD (ASSM) AND THE CONTINUOUS SUN-AND-SHADE METHOD (CoSSM)

X6.1 The fundamental difference between the ASSM and the CoSSM is the use of direct solar radiation in the former and hemispherical solar radiation in the latter case.

X6.2 The advantages and disadvantages of these methods arise from:

X6.2.1 *Instrument Cost*—The CoSSM needs one more reference pyranometer than the ASSM. However, the shade disc device for measuring the diffuse radiation can be very carefully fitted to the pyranometer and the view geometry of the standard pyrheliometer. In the case of the ASSM, the shade disc device has to be combined with field pyranometers having various sizes of domes and receiver surfaces.

X6.2.2 *Data Acquisition System*—The ASSM needs only two millivolt channels, namely for recording the direct and the hemispherical solar irradiances; electrical offset in the channel of the latter is eliminated by the evaluation procedure (see Eq 2).

X6.2.3 *Selection of Site*—In the case of the ASSM, the ground-reflected hemispherical radiation and the effect of obstructions on the readings is eliminated by the evaluation procedure. When using the CoSSM, the measuring site for the test and the reference pyranometers must be selected so that both instruments have nearly identical fields of view.

X6.2.4 *Operational Procedure*—When using the ASSM, the periodic setting of the shade disc requires manual operation, or the automatic operation of a relatively expensive tracking device. However, the continuous shading of the pyranometer in the case of CoSSM can be established by a relatively simple automatic sun-tracking device, as shown for instance in Fig. X1.4.

X6.2.5 *Data Rate:* With the CoSSM, the sampling frequency depends mainly on the reading conditions of the standard pyrheliometer; in the case of ASSM, the time response of the pyranometer and the required degree of approximation to the theoretical final value (see 5.6.2) determine the reading interval. Generally, therefore, the CoSSM delivers series with more data and better statistics than the ASSM.

X6.2.6 *Measurement Conditions:* Since the radiometric quantities $E_{G,\beta}$, $E_{D,\beta}$ and E_I are read nearly simultaneously, the CoSSM can be also used on days with less stable sky conditions. In the case of ASSM, the $E_{D,\beta}$ value at the reading of $E_{G,\beta}$ is determined by interpolation between the previous and following $E_{D,\beta}$ values. A modification of ASSM to obtain simultaneous readings of $E_{D,\beta}$ in the data sets is described in Appendix X5.

X6.2.7 *Applicability of Calibration Factors:* Owing to the continuous exposure of the test pyranometer with the CoSSM, the derived calibration factor should apply to data measured under clear sky conditions.

X6.2.8 Owing to the alternating exposure of the test pyranometer with the ASSM, the derived calibration factor should apply to data measured under scattered cloud conditions.

REFERENCES

(1) WMO, OMM No. 8 Guide to Meteorological Instruments and Methods of Observation, 7th ed., OMM Vol No. 8, 1983, Geneva, Switzerland, Secretariat of the World Meteorological Organization.

(2) Angström, A. and Rodhe, B., "Pyrheliometric Measurements with Special Regards to the Circumsolar Sky Radiation," *Tellus*, XVII, (1), 1966.

(3) Anonymous, Pyrheliometer Comparisons 1980 IPC V Results and Symposium. Working Report No. 94. Swiss Meteorological Institute, Davos and Zurich Switzerland, February 1981.

(4) Anonymous, Pyrheliometer Comparisons 1985 IPC VI Results and Symposium. Working Report No. 137. Swiss Meteorological Institute, Davos and Zurich Switzerland, December 1985.

(5) Anonymous, International Pyrheliometer Comparison IPC VII, 1990 Results and Symposium, Working Report No. 162. Swiss Meteorological Institute, Davos and Zurich Switzerland, March 1991.

(6) Anonymous, International Pyrheliometer Comparison IPC VIII 1995 Results and Symposium, Working Report No. 188. Swiss Meteorological Institute, Davos and Zurich Switzerland, May 1996.

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

(8) Gulbrandsen, A., " On the Use of Pyranometers in the Study of Spectral Solar Radiation and Atmospheric Aerosols," *Journal of Applied Meteorology*, 17, 1978, pp. 899-904.

(9) Dutton, E. G., Michalsky, J. J., Stoffel, T., Forgan, B. W., Hickey, J., Alberta, T. L., and Reda, I., "Measurement of Broadband Diffuse Solar Irradiance Using Current Commercial Instrumentation with a Correction for Thermal Offset Errors," *Journal of Atmospheric and Oceanic Technology*, 18 (3), 2001 , pp. 297-314.

(10) Haeffelin, M., Kato, S., Smith, A. M., Rutledge, C. K., Charlock, T. P., and Mahan, J. R., "Determination of the Thermal Offset of the Eppley Precision Spectral Pyranometer," *Applied Optics*, 40(4), 2001, pp. 472-484.

(11) Philipona R., " Underestimation of Solar Global and Diffuse Radiation Measured at the Earth's Surface," *Journal of Geophysical Research*, 107(D22), 2002, pp. ACL 15.1–ACL 15.8.

(12) Reda, I., et al., " Using a Blackbody to Calculate Net-Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Thermal Offset During Outdoor Calibration Using the Component Sum Method," *Journal of Ocean Atmosphere Technology*: Vol. 22, No. 10, October 2005, pp. 1531–1540.

(13) Myers, D. R., Reda, I., Wilcox, S., and Andreas, A., "Optical Radiation Measurements for Photovoltaic Applications: Instrumentation Uncertainty and Performance," in 50th Annual Conference of the Society of Photo-optical Instrumentation Engineers, Organic Photovoltaics V. 2004. Denver, CO, SPIE Bellingham, Washington.

(14) Reda, I., Stoffel, T., and Myers, D., "A Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance," *Solar*

Energy, 74, 2003, pp. 103-112.

(15) Zerlaut, G. A., *Solar Radiation Instrumentation, Solar Resources*, ed. R. Hulstrom, The MIT Press, Cambridge, MA, 1989.

(16) Michalsky, J., " The Astronomical Almanac's Algorithm for Approximate Solar Position (1950-2050)," *Solar Energy*, 40(3), 1988, pp. 227-235.

(17) Michalsky, J., " Errata: The Astronomical Almanac's Algorithm for Approximate Solar Position (1950-2050)," *Solar Energy*, 41(1), 1988, p. 113.

(18) Reda, I., and Andreas, A., "Solar Position Algorithm for Solar Radiation Applications," *Solar Energy*, 76, 2004, pp. 577-589.

(19) 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.

(20) 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

(21) United Kingdom Accreditation Service (UKAS), The Expression of Uncertainty and Confidence in Measurements, M3003, 3rd edition. Feltham, Middlesex, UK, 2012. Available on the World Wide Web at http://www.ukas.com/Library/Technical-Information/Pubs-Technical-Articles/Pubs-List/M3003_Ed3_final.pdf

(22) SAC-SINGLAS Technical Guide 1, Guidelines on the Evaluation and Expressing of the Measurement Uncertainty, 2nd Ed., March 2001.

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