Standard Test Method for Calibration of Reference Pyranometers With Axis Tilted by the Shading Method[1]

This standard is issued under the fixed designation E 941; 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 the total global (hemispherical) irradiance of sunlight are required in (*a*) the determination of the energy available to flat plate solar collectors, (*b*) the assessment of irradiance and radiant exposure in the testing of solar and nonsolar-related materials technologies, and (*c*) the assessment of the direct solar versus diffuse sky components for energy budget analysis, geographic mapping of solar energy, and as an aid in the determination of the concentration of aerosol and particulate pollution, and water vapor effects.

The method described herein requires calibration to the World Radiation Reference Scale (also known as the Absolute Radiometric Scale); traceability to the International Pyrheliometric Scale of 1956 shall not be permitted.

The intercomparison of absolute radiometers, on which the Absolute Radiation Scale depends, is covered by procedures adopted by the World Meteorological Organization (Geneva) and by various U. S. intercomparisons, chief among which are the New River intercomparisons of absolute cavity polar pyrheliometers held on Nov. 1 to 3, 1978. These intercomparison procedures are not covered by this test method.

Although meteorological surveys require calibration of pyranometers oriented with axis vertical, applications associated with flat plate collectors and the study of the solar exposure of related materials require calibrations of instruments tilted at predetermined nonvertical orientations. These calibrations at fixed tilt angles have applications which seek state-of-the-art accuracy requiring the use of cosine, tilt, and azimuth corrections.

1. Scope

1.1 This test method covers all pyranometers having calibrations sensitive to tilt.

1.2 This test method combines measurement and calculation, yielding calibration factors derived from many measurements and identified with either a single tilt angle or at normal incidence with one or only a few specific angles of tilt.

1.3 This test method is applicable to reference pyranometers regardless of the radiation receptor employed.

1.4 Two types of calibrations are covered: Type I employs a self-calibrating pyrheliometer, and Type II calibrations employ a secondary reference pyrheliometer as the standard instrument.

1.5 This test method provides for calibration at fixed south facing tilts from the horizontal with instrument constant data obtained at various angles of incidence throughout the day at that tilt.

1.6 Calibration of reference pyranometers may be performed by a method in which the axis of the sensitive element is aligned with the sun during the shading disk test. This procedure avoids the effect of cosine errors, but emphasizes the importance of tilt corrections.

1.7 The calibration of reference pyranometers at horizontal, that is, with axis vertical, is covered in another ASTM standard (see Section 2).

1.8 This test method is applicable only to calibration procedures using light from the sun.

2. Referenced Documents

2.1 *ASTM Standards:*

E 44 Definition of Terms Relating to Heat Treatment of Metals[2]

E 772 Terminology Relating to Solar Energy Conversion[3]

E 816 Method for Calibration of Secondary Reference Pyrheliometers and Pyrheliometers for Field Use[4]

[1] This test method is under the jurisdiction of ASTM Committee G-3 on Durability of Nonmetallic Materialsand is the direct responsibility of Subcommittee G03.09.

Current edition approved April 29, 1983. Published August 1983.

[2] *Annual Book of ASTM Standards*, Vol 01.02.

[3] *Annual Book of ASTM Standards*, Vol 12.02.

[4] *Annual Book of ASTM Standards*, Vol 14.04.

E 824 Method for Transfer of Calibration from Reference to Field Pyranometers[4]

E 913 Method for Calibration of Reference Pyranometers with Axis Vertical by the Shading Method[4]

Method for Calibration of Reference Pyranometers with Respect to Cosine, Tilt and Azimuth Errors[5]

2.2 *Other Documents:*

Guide to Meteorological Instruments and Observing Practices WMO, 1965[6]

3. Definitions

3.1 *altazimuthal mount*—a tracking mount capable of rotation about orthogonal altitude and azimuth axes; tracking may be manual or by a follow-the-sun servomechanism. (See also Terminology E 772).

3.2 *direct beam irradiation*—that component of solar irradiance within the solid angle subtended by the sun at the observer. (See also the definition for "solar irradiance, direct" in Terminology E 772.)

3.3 *equatorial mount*—see Terminology E 772.

3.4 *solar irradiance, global*—see Terminology E 772.

3.5 *pyranometer*—see Terminology E 772.

3.6 *pyranometer, field*—a pyranometer essentially meeting WMO Class II specifications or better (that is, Class I), appropriate to field use and typically exposed continuously.

NOTE 1—The WMO Classification of Pyranometers and Pyrheliometers is currently under study and may be eliminated altogether by WMO.

3.7 *pyranometer, reference*—a pyranometer essentially meeting WMO Class I specifications and used principally to calibrate other instruments.

3.8 *pyrheliometer*—a radiometer used to measure the direct beam irradiance incident on a surface normal to the sun's rays. (See Terminology E 772.)

3.9 *pyrheliometer, absolute (self-calibrating)*—a radiation sensor for determining the direct solar irradiance having a field of view of 5 deg and a slope angle of 0.75 to 0.8 deg and having a blackened cavity receiver for absorption of the incident radiation; the measured electrical power in a heater affixed to the cavity receiver constitutes the method of self calibration and traceability to absolute SI units; the sensing of the temperature rise of the receiving cavity is employed to either relate the radiation quantity to the SI electrical quantity (passive) or to control the heater to stabilize cavity temperature at a desired set-point (active).

3.10 *pyrheliometer, secondary reference*—a pyrheliometer essentially meeting WMO Class I specifications, but not having self-calibrating capability.

3.11 *tilt angle,* θ—the angle between the vertical and the pyranometer axis. This quantity is also the angle between the horizontal and the plane of the detector surface.

4. Summary of Test Method

4.1 The reference pyrheliometer is mounted on a sun tracker designed to maintain the instrument axis pointing directly toward the sun. The pyranometer being calibrated, that is, the test instrument, is mounted either on a south-facing platform fixed at a specified tilt from the horizontal, or on the same or separate tracker and aligned with axis pointed toward the sun (for normal incidence calibration). An adjustable and removable opaque disk is provided which, when suitably positioned, can be made to shade the pyranometer dome and sensor assembly from the direct solar radiation. A second pyranometer of the same type is also mounted in the same plane as the test pyranometer, but is not shaded. Readings from the second pyranometer will be used to resolve any inconsistencies in the test data, by providing a record of sky variability.

4.2 The direct solar irradiance on a surface normal to the sun is measured and recorded together with the corresponding zenith angle.

4.3 The test pyranometer is alternately shaded and unshaded. The millivolt outputs from the test pyranometer, shaded and unshaded, provide, by difference, the millivolt signal corresponding to the direct solar irradiance on the tilted surface of the detector.

4.4 The calibration value in each of the test measurements at fixed south-facing tilts is the factor, kC_θ, in the following:

$$kC_\theta = ((V_u - V_s)/(I_d \cos\ \theta)/V \cdot w^{-1} \cdot m^2 \quad (1)$$

where:

O = incident angle of the direct radiation on the pyranometer,
I_d = direct irradiance on a surface normal to the sun,
V_u = signal voltage unshaded,
V_s = signal voltage shaded, and
C_θ = cosine corection factor (deviation from Lambert's Cosine Law) that makes "*k*" largely independent of θ.
m = metric
w = weight

If C_θ is not known, it is taken as unity. The determination of incident angle effects is the subject of another ASTM standard under development.

4.5 The calibration value for the normal incidence condition, that is, with the axis coaligned exactly with the direct component, is computed as follows:

$$k = (V_u - V_s)/(I_d)/V \cdot w^{-1} \cdot m^2 \quad (2)$$

In this case, the instrument is calibrated only at those tilt angles which the elevation of the sun will permit.

5. Significance and Use

5.1 Tilted, the pyranometer is an instrument designed to measure the sum of direct solar radiation and sky radiation incident on a tilted surface, that is, the detector, in such proportions as solar altitude, cloud cover, and foreground albedo may produce.

5.2 The method described represents the only practical means for calibration of a tilted reference pyranometer and employs a standard reference pyrheliometer. While the suntrackers, the shading disk, the number of instantaneous readings, and the electronic display equipment used will vary from instrument to instrument and from laboratory to laboratory, the method provides for the minimum acceptable conditions, procedures, and techniques required.

[5] These standards are available in draft form only. For copies, contact the Standards Development Division, ASTM, 1916 Race St., Philadelphia, PA 19103.

[6] World Meteorological Organization, No. 8 TP3 Supplement No. 5, August 1975.

5.3 While, in theory, the choice of tilt angle is unlimited, in practice, satisfactory precision is achieved over a range of tilt angles close to the zenith angles used in testing.

5.4 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 is required to relate the calibration to other orientations, including axis vertical.

5.5 Traceability of calibration to the reference pyrheliometer represented by one or more of the following is accomplished when employing the method and when meeting the requirements associated therewith:

5.5.1 International Pyrheliometric Comparisons IV and V, Davos, held in 1975 and 1980, respectively, with PACRAD III and PMO2 being primary reference instruments of WMO **(1).**[7]

5.5.2 One of the New River Intercomparisons of Absolute Cavity Solar Pyrheliometers (two of which were International) with TMI/Kendall 67502 being the primary reference standard of the NOAA Solar Radiation Facility/Boulder **(2).**

5.5.3 Any future intercomparison of comparable reference quality.

5.5.4 Any of the absolute radiometers participating in the above intercomparisons and being within ±0.5 % of the mean of all similar instruments compared in any of those intercomparisons.

5.6 The calibration method employed assumes that the accuracy of the values obtained are independent of time of year within the constraints imposed and by the test instrument's temperature compensation (neglecting cosine errors).

6. Apparatus

6.1 *Digital Electronic Readout*—Any digital microvoltmeter with precision of ±0.1 % of average reading, and uncertainty of ±0.2 % may be employed. Printing data loggers having print-out must be capable of a measurement frequency of at least 2/min. A data logger having at least three-channel capacity may be useful.

6.2 *Pyranometer*—A pyranometer meeting the WMO Class I specification **(6)** for such instruments shall be employed as the test instrument (which then may be employed as a primary reference pyranometer in Test Method E 824 to transfer calibration to field pyranometers.

6.3 *Pyranometer, Monitoring*—A pyranometer nominally meeting WMO Class I specifications employed to monitor the sky variability during calibration.

6.4 *Self-calibrating Absolute Cavity Pyrheliometer*[8]—A self-calibrating absolute cavity pyrheliometer identified as "primary" shall be an instrument that has either participated in one of the intercomparisons listed in 5.5 of this test method, or that has been intercompared with any one of the absolute cavity radiometers that participated in those intercomparisons. If the primary reference carried indirect traceability to one or more of the intercomparisons, it shall have been determined to read within ±0.5 % of the mean of the intercomparison to which it is traceable. Calibrations referenced to an absolute instrument are designated as Type I.

NOTE 2—The Absolute Cavity Pyrheliometer has an unobstructed aperture. Hence, no question arises concerning the spectral transmission of window materials.

6.5 *Secondary Reference Pyrheliometer*[9]—The secondary reference pyrheliometer when employed for a Type II calibration shall be of suitable quality in terms of linearity of response, sensitivity, stability of response, and temperature compensation such that it meets or exceeds the specifications of a WMO Class I pyrheliometer **(6).** The principal additional requirement is that it shall have been calibrated within 6 months by the procedures presented in ASTM E44, utilizing an instrument such as defined in Section 5 and 6.4.

6.6 *Shading Disk*—A blackened circular disk with a diameter of 88 to 100 mm shall be mounted at the end of a slender, rigid blackened rod that is held by a rigid blackened slender post such that the distance between the disk and the test pyranometer specified in 6.2 is 1 m (±5 mm). The disk and rigid support must be so positioned that the disk will just shade the entire receiver and outer transparent hemispherical enclosure. This will require an ability to vary the length of each of the mounting rods. Either mounting fixture should be designed to permit easy and rapid positioning of the shading disk perpendicular to the direct solar radiation. A suggested configuration is shown in Fig. 1. The purpose of these dimensions and adjustments is to create a geometry such that the opening angle of the shaded pyranometer is essentially the same as that of the reference pyrheliometer employed. When used with the self-calibrating pyrheliometer, the disk diameter should be 88 mm.

6.7 *Sun Tracker(s)*,[10] whether power driven or manually operated, or a servo-operated altazimuth mount, shall be employed to properly align the reference pyrheliometer normal to the sun for the entire test period. The tracking precision shall be such that the pyrheliometer is aimed properly at the sun for all data-taking periods as demonstrated by an optical alignment system on the pyrheliometer or the tracker. The pyranometer under calibration requires either an altazimuth mount or an equatorial sun-tracking mount for normal incidence calibrations.

6.8 *Adjustable Platform*—For calibrations at fixed south-facing tilts, a platform adjustable in azimuth and altitude (tilts from the horizontal) to an accuracy of better than 0.5 deg shall be employed.

7. Interferences and Precautions

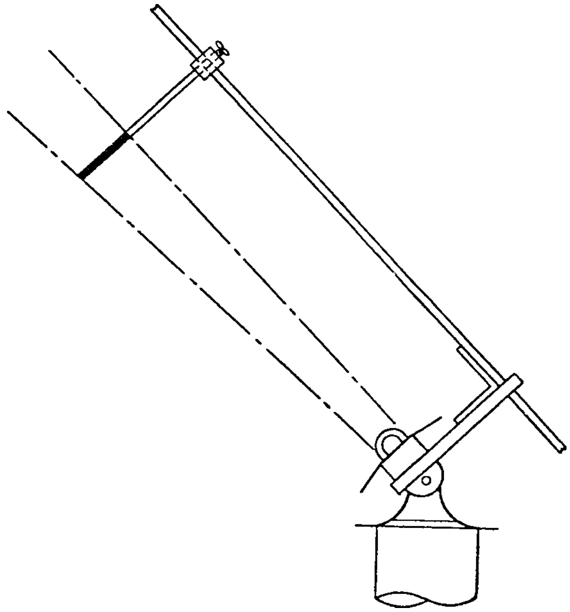
7.1 *Sky Conditions*—The measurements made in determining the instrument constant shall be performed only under conditions when the sun is unobstructed by clouds for an incremental data-taking period. The minimum acceptable direct solar irradiance on the tilted surface, given by the product

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

[8] Suitable self-calibrating absolute cavity pyrheliometers are the Mark VI manufactured by Technical Measurements, Inc., La Canada, CA 91011 **(3)**, and the Eppley Model HF manufactured by The Eppley Laboratories, Inc., 33 Sheffield Ave., Newport, RI 02848 **(4)**. Active cavity radiometers (ACRs) are also suitable **(5)**.

[9] A suitable secondary reference pyrheliometer is an Eppley Model NIP pyrheliometer manufactured by The Eppley Laboratories, Inc.

[10] Suitable trackers are manufactured by The Eppley Laboratories, Inc. and Technical Measurements, Inc.



NOTE 1—Actual numbers shown are for a typical Eppley PSP with a first time constance of 1 s.

FIG. 1 Shading Disk Arrangement

of the pyrheliometric measurement and the cosine of the incident angle, shall be 80 % of the global solar irradiance. Also, no cloud formation shall be within 30 deg of the sun during the period that data are taken for record.

7.2 *Instrument Orientation Corrections*—The irradiance calibration of the 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 pyranometer with cable connector uppermost.

7.2.1 *Cosine Corrections*—This test method permits the pyranometer to be tested with axis directed toward the sun; in this case, there are no cosine errors during calibration and during use as a transfer instrument in the tilted mode. The incident angles and hence the cosine corrections are small in most applications. When the pyranometer is calibrated at a fixed tilt, 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. The calibration uncertainty will be minimized if the correction is known; otherwise the correction is taken as unity.

7.2.2 *Azimuth Corrections*—Although this test method requires the pyranometer to be oriented with cable connector uppermost, the incident angle corrections may include azimuth corrections. Cosine and azimuth corrections are covered by another ASTM standard under development.

7.3 *Environmental Conditions*—Under general conditions of both calibration and use, the pyranometer output 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 method or the control of the practitioner. This topic is discussed in more detail in the Appendix.

7.4 *Deviations of the Reference Pyranometer from a Perfect Pyranometer*—A perfect pyranometer is one which evaluates the incident irradiance correctly and reports a correct single number repesenting the total irradiance integrated over the instrument's field of view regardless of the spatial distribution of the irradiance and the orientation of the pyranometer in azimuth and tilt. This perfection may stem from instrument design and construction, experimentally determined correction factors, or a combination thereof.

7.5 *Time Measurement*[11]—Some measurements will be taken at high solar altitudes and high angles of tilt. Under these conditions, accurate timekeeping and the difference between local time and zone time may be important.

7.6 The reference pyrheliometer(s) shall not be used as a field instrument and its exposure to sunlight shall be limited to calibration or intercomparisons.

NOTE 3—At a laboratory where an absolute cavity pyrheliometer is not available, it is advisable to maintain a group of two or three reference pyrheliometers which are included in every calibration. These serve as controls to detect any instability or irregularity in any of the reference instruments.

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

7.8 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 sunlight onto the calibration facility. When calibrating at tilt angles from the horizontal, the foreground shall be selected so as to not reflect sunlight onto the test facility from materials, objects, etc.

[11] Accurate time is provided by the National Institute of Standards and Technology through WWV, Boulder, CO. Electronic stores sell completely adequate time cube radios for this purpose.

8. Procedure

8.1 *Mounting*:

8.1.1 Mount the self-calibrating absolute cavity pyrheliometer (hereinafter designated the primary reference pyrheliometer) or a secondary reference pyrheliometer (if a Class II shading calibration is desired) to either an altazimuth or equatorial sun tracker. Align the sun tracker with a solar-noon south reference (and level the tracker with the "bubble level" provided if an equatorial mount is employed). Set the latitude angle adjustment of the equatorial tracker to the exact local latitude. Align the reference pyrheliometer with the sight device provided.

8.1.2 Mount the test pyranometer on either the adjustable platform or the platform of an altazimuth, or equatorial tracker. With the platform tilted, rotate the case until the instrument cable connector faces up. Mount the second, monitoring pyranometer adjacent and coplanar with the test pyranometer. Adjust the platform to exactly horizontal and level each pyranometer with the leveling screws and bubble level provided. Adjust the platform for the calibration conditions required (that is, fixed angle or tracking normal incident).

8.1.3 Connect the reference, monitoring, and test instruments to their respective, or common, digital voltmeter, using proper shielding. Check out the instruments for electrical continuity, polarity of the signal, and the nominal signal strength and stability. (An analog strip chart or $X - Y$ recorder for the monitoring unit signal is suggested.)

8.1.4 If a Class I calibration is desired, calibrate the self-calibrating absolute cavity pyrheliometer in accordance with the procedure required for that particular absolute radiometer and record the irradiance for each instantaneous reading. If a Class II calibration is desired, compute the irradiance for each instantaneous reading by dividing the signal from the secondary reference pyranometer by its instrument constant.

8.2 *Shading Disk Alignment*:

8.2.1 Mount the shading disk apparatus such that all posts and mounts are north of the test pyranometer. Ensure that no mounting brackets or paraphernalia subtend more than a very small portion of the north sky. Adjust the shading disk to be 1 m distant from the test pyranometer's receiver in such a manner that the shadow just completely covers the outermost hemispherical transparent enclosure. Provide means for moving the disk in and out of the shading condition rapidly and accurately.

8.3 *Determination of Thermopile Time Constant*—Illuminate the pyranometer for 10 min (unshaded) and record the signal V_u. Then shade the pyranometer for 60 s and record the signal V_s. Unshade the pyranometer and, taking continuous voltage readings, determine the time required for the response signal to reach *l/e* (63 %) of the final steady state value V_u. Record the time, t_c, as the instrument constant.

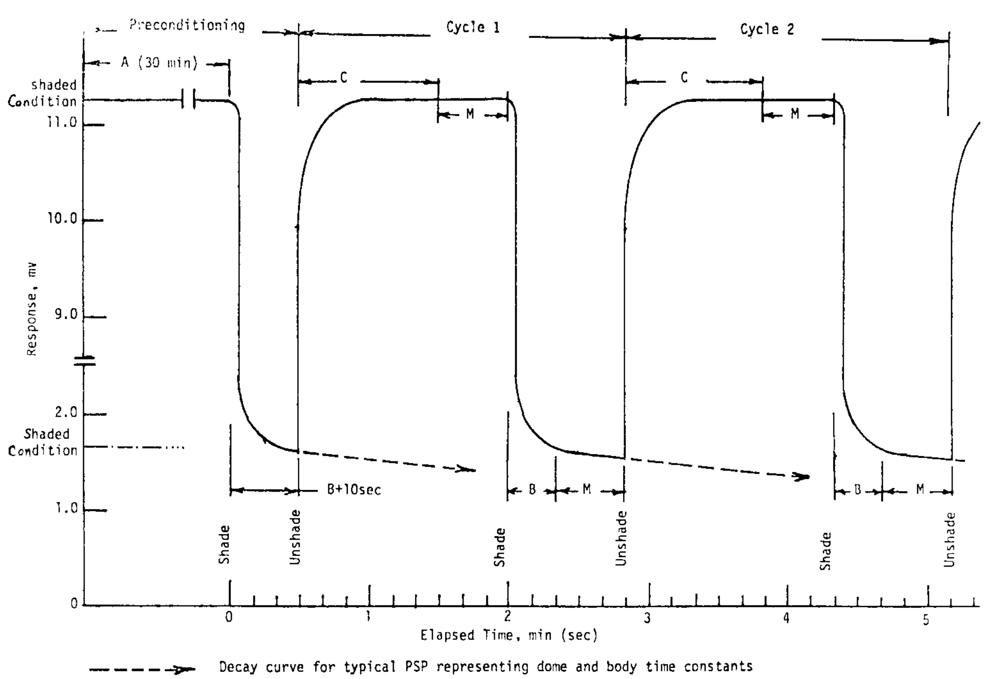
NOTE 4—Eppley Model PSPs have time constants of 1 s.

8.4 *Data-Taking Sequence*:

8.4.1 Allow 30-min warmup of all instruments before taking data. Precondition the test pyranometer by exposing in the unshaded mode during this 30-min period as shown in Fig. 2 (*A*). Ensure that the data-taking sequence takes place during cloud-free conditions.

8.4.2 Adjust shading disk and prepare to take the readings prescribed in 8.4.3.

8.4.3 At the completion of the unshaded (illuminated) preconditioning soak period (Fig. 2 (*A*)), shade the pyranometer for 20 to 30 time constants, *B*. This completes the first preconditioning cycle.



NOTE 1—Actual numers shown are for a typical Eppley PSP with a first time constant of 1 s.

FIG. 2 Shade/Unshade Timing Sequence for Shading Disk Calibration of Pyranometers

NOTE 5—The preconditioning cycle is required to stabilize the temperature of the case and dome prior to taking data.

8.4.4 Take data in accordance with the sequence of unshaded and shaded conditions shown in Fig. 2. Repeat the shaded-unshaded sequence for a total of 5 cycles. Each cycle represents first 60 time constants, *C*, of full illumination (unshaded) followed by 30 s of data taking, *M*, during which not less than three instantaneous readings of the pyranometer response, V_u, are recorded, then 20 time constants of *B* with the beam component shaded, followed by 30 s of data taking, *M*, during which not less than three instantaneous readings of the pyranometer response, V_s, are recorded. Take not less than three instantaneous readings of the direct irradiance during each data-taking segment, *M*, employing the reference pyrheliometer chosen.

8.4.5 Perform the sequence of 5 cycles shown in Fig. 2 over a sufficient number of days such that at least one sequence is obtained for each hour from 0800 to 1600 h apparent solar time (or to limits defined by the requirement to take data at zenith angles of at least 60 deg).

NOTE 6—At certain times of the year and under certain conditions it may be possible to complete the sequence in one day. Also, by distributing the data throughout a day, incident angle effects (cosine and azimuth) can be obtained.

8.4.6 Take not less than three instantaneous readings of V_u with an unshaded monitoring pyranometer for each period of data taking *M*. Record as V_o.

8.5 *Data Recording and Calculation*:

8.5.1 In each sequence when calibrating at fixed tilts, use the form of worksheet shown in Fig. 3 to record alternative and consecutive values of V_u, the test instrument signal in the unshaded condition, V_s, the test instrument signal in the shaded condition, V_o, the signal from the unshaded pyranometer, I_d, the direct irradiance, cos θ, the cosine of the angle of incidence, and the time. Use the form of the worksheet shown in Fig. 4 when calibrating at exactly normal incidence.

8.5.2 For each test scan compute θ and cos θ from the following:

$$\cos\theta = [\sin\delta\sin\phi\cos\beta] - [\sin\delta\cos\phi\sin\beta] + [\cos\delta\cos\phi\cos\beta\cos\omega] + [\cos\delta\sin\phi\sin\beta\cos\omega] \quad (3)$$

where:

θ = incident angle of the direct radiation on the pyranometer,
φ = station latitude,
δ = solar declnation = 23.45 sin[0.9863(*n* + 283.4)] (with *n* being the day of the year),
β = tilt angle of the pyranometer axis from the vertical, and
ω = hour angle from solar noon, with solar noon being zero, and each hour equaling 15 deg of longitude with mornings negative and afternoons positive (for example, *H* = −15 for 11:00, and *H* = + 37.5 for 4:30).

8.5.3 From the mean value of the incident angle calculated

PYRANOMETER WITH AXIS AT FIXED TILT
TEST WORK SHEET

DATE______ RUN NO.______ AVG.θ______ Cθ______ TILT ANGLE ______
R.H.______% TEMPERATURE______°C

Time Limit	Incident Angle θ	Cos(θ)	I_d	V_u	V_s	V_o	C_θ
MEAN							
S. D.							

$$K = \frac{(V_u - V_s)}{C_\theta I_d \cos\theta}$$

K = ______

FIG. 3 Test Work Sheet for Pyranometer with Axis at Fixed Tilt

PYRANOMETER WITH AXIS TILTED AT EXACTLY NORMAL INCIDENCE
TEST WORK SHEET

DATE________ RUN NO.________ AVG. z____________
R.H. __________% Temperature__________°C

TIME	I_d	V_u	V_s	V_o
MEAN				
S. D.				

$k_x = (V_u - V_s)I_d$

FIG. 4 Test Work Sheet for Pyranometer with Axis Tilted at Exactly Normal Incidence

for each sequence in accordance with 8.5.2, compute I_d cos θ, the solar irradiance projected on the tilted surface. List appropriate values of C_θ, the instrumental cosine correction factor, if available; otherwise, enter the value 1.000.

8.5.4 Compute *k*, the instrument constant for each sequence, from the following:

$$k = (V_u - V_s/C_\theta I_d \cos \theta \; V \cdot w^{-1} \cdot m^2 \quad (4)$$

Assemble all *k* values. Plot the *k* values as a function of angle of incidence as shown in Fig. 5. Select as the instrument constant the *k* value representing the weighted average of *k* values for the incident angles that will be encountered in end-use applications. For resource assessment purposes, the *k* value at incident angles represented by a solar altitude of 60 deg may be the best weighted value for the continental United States on an annual basis.

NOTE 7—For the special case of shading disk calibration at normal incidence, Eq 4 reduces to $k = (V_u - V_s)/I_d$ and Eq 3 and Eq 4 are not needed.

9. Report

9.1 The report shall include as a minimum the following information:

9.1.1 Instrument type,

9.1.2 Manufacture and model number,

9.1.3 Instrument serial number,

9.1.4 Date of calibration(s),

9.1.5 Scale (absolute),

9.1.6 Latitude, longitude, and altitude (m),

9.1.7 Calibration class,

9.1.8 Mean value of instrument constant

$$k = V \cdot \mathrm{w}^{-1} \cdot \mathrm{m}^2 \text{ at deg tilt} \quad (5)$$

9.1.9 Standard deviation,

9.1.10 Range of zenith angles, and

9.1.11 Traceability (a concise statement of the hierarchy of traceability including SN of secondary or primary pyrheliometer).

10. Precision and Bias

10.1 The precision achievable in determining the instrument constant of a reference pyranometer tested with axis tilted is influenced by sky conditions because the shaded and unshaded measurements are made consecutively rather than simultaneously. This uncertainty is most severe at low solar elevations where the zenith angle is changing rapidly with time. Repeatability within any test sequence performed at or near solar noon should be such that the standard deviation is less than ±0.4 % of the mean of the shaded and unshaded voltages tabulated on the work sheet (Fig. 3). Substantially larger standard deviation may be observed under certain meteorological conditions. For example, high, thin cirrus clouds nearly invisible to the naked eye, may cause rapid variation in the diffuse irradiance. Superior calibrations are obtained when the meteorological conditions are stable as evidenced by small standard deviation in the measurements.

10.2 The uncertainty of the absolute value of the on-axis flux calibration to be expected when calibrating pyranometers

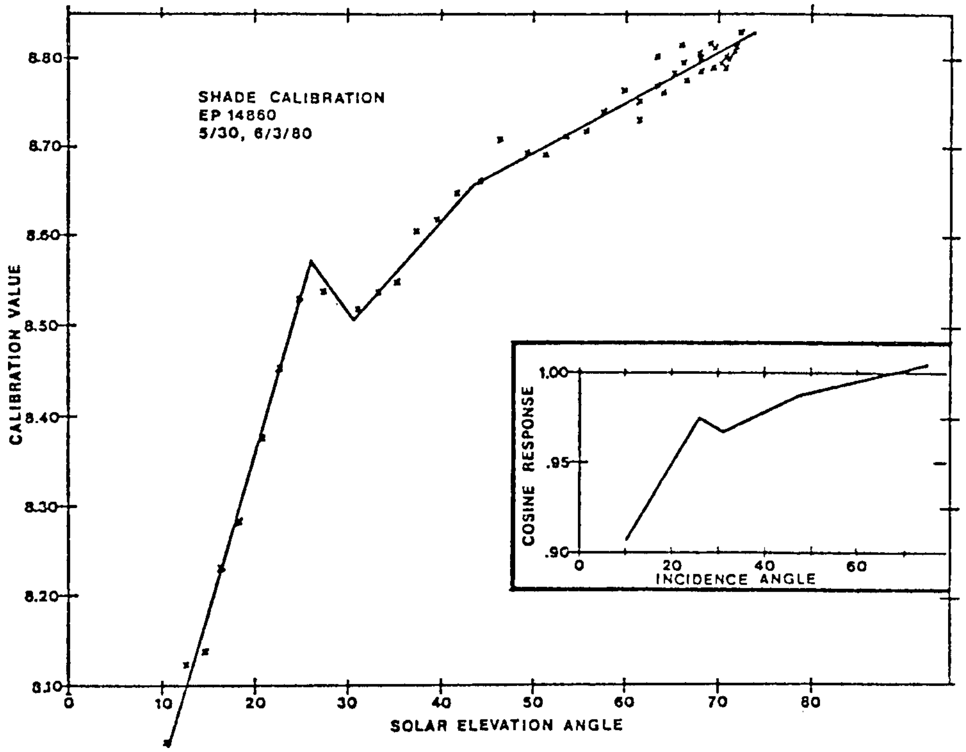


FIG. 5 Example of Shading Disk Calibration Values for an Eppley PSP Pyranometer as a Function of Solar Elevation Angle

with axis tilted by the shading disk method depends on (*a*) the accuracy of the reference pyrheliometer calibration, (*b*) the accuracy of the transfer to the pyranometer, (*c*) the accuracy of the time and angle determinations, and (*d*) the accuracy of the pyranometer's tilt correction. Of these, the tilt correction has the least support from experiment.

10.3 The bias of transfer at tilt from a reference to a field pyranometer is influenced by the transfer of flux sensitivity and by the degree to which the reference and field instrument properties depart from those of a perfect pyranometer (7.4).

10.4 The standard deviation assigned to the calibration constant reported in Section 9 indicates a lower bound on variability. The actual value may be higher because of biases which this standard deviation does not disclose.

APPENDIX

(Nonmandatory Information)

X1. DISCUSSION OF ENVIRONMENTAL CONDITIONS

X1.1 In addition to the direct and diffuse solar irradiances to which a pyranometer responds, it is also sensitive to many conditions which can be discussed as environmental parameters. For the direct application of this discussion to this test method, see 7.2-7.4.

X1.2 The functional dependence, *f*, on some of the better understood parameters may be written as follows:

$$S = f(\lambda, \theta, \phi, \psi, T, G, T, P, \Delta T_n) \quad \text{(X1.1)}$$

where:

S = output,
λ = wavelength of incident radiation (spectral flatness),
θ = angle of source with respect to receiver normal (cosine response, 0 to 90 deg),
ϕ = angle to source about axis of receiver (azimuthal dependence),
ψ = angle between normal of instrument and local normal (tilt dependence, including convective effects),
$\dot{T}$ = thermal transients, change of temperature (of heat sink, etc.) with respect to time,
P = pressure (pressure dependence of thermal conductivity of air),
G = irradiance level at receiver (linearity of response), and

ΔT_n = gradients and temperature differences within the instrument case, or heat sink.

X1.3 Many experiments are needed to characterize the functional dependence of those factors which are orthogonal, such as tilt, cosine, and azimuth dependence, and allow the following equation:

$$f(\lambda, \theta, \phi, \psi, T, G, T, \Delta T_n) = h(\theta) \times g(\phi) \times k(\psi) \times f(\lambda...) \quad \text{(X1.2)}$$

where:

h, *g*, and *k* are functions which may be determined or found by experiment and used to make appropriate corrections to data. The remaining parameters can make significant contributions to instrument error if they are not understood, or their existence is ignored.

X1.4 Particular attention needs to be paid to those terms which are dependent on the same parameter as the basic principle of the instrument, namely on temperature *T*, difference in temperature ΔT, and temperature gradients ΔT_n. For example, calibrating and using a pyranometer at a tilt with improper mounting may lead to temperature effects which override and mask out effects due to tilt alone, which the operator feels may have been" calibrated out" using a tilt correction factor technique.

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