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

This standard is issued under the fixed designation G 167; 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 Test Method E 913 dealing with the calibration of pyranometers with axis vertical and Test Method E 941 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 E 842.

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 equitorial 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:*

E 772 Terminology Relating to Solar Energy Conversion[2]

E 824 Method for Transfer of Calibration from Reference to Field Radiometers[3]

E 913 Test Method for Calibration of Reference Pyranometers with Axis Vertical by the Shading Method[3]

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

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

[3] *Annual Book of ASTM Standards*, Vol 14.02.

E 941 Test Method for Calibration of Reference Pyranometers with Axis Tilted by the Shading Method[3]

2.2 *WMO Document:*

World Meteorological Organization (WMO), "Measurement of Radiation" Guide to Meteorological Instruments and Methods of Observation, fifth ed., WMO-No. 8, Geneva[4]

2.3 *ISO Standards:*

ISO 9060:1990 Solar Energy - Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation[4]

ISO 9846:1993 Solar Energy - Calibration of a Pyranometer Using a Pyrheliometer[4]

3. Terminology

3.1 *Definitions*:

3.1.1 See Terminology E 772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *altazimuth mount*—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*—determination of the responsivity (or the calibration factor, as its reciprocal) of a radiometer under well-defined measurement conditions.

3.2.3 *direct solar radiation*—that component of solar radiation within the solid angle subtended at the observer by the sun's solar disk plus arbitrarily defined portion of the circumsolar radiation.

3.2.4 *diffuse solar radiation*—that component of solar radiation reaching the earth as a result of being scattered by the air molecules, aerosol particles, cloud and other particles.

3.2.5 *equitorial mount*—see Terminology E 772.

3.2.6 *field of view angle of a pyrheliometer*—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 aperture, if the latter are circular and concentric to the receiver surface; if not, effective angles may be calculated.[5]

3.2.7 *global solar radiation*—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 Sr.

3.2.8 *hemispherical radiation*—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 limiting case of a horizontal surface is denoted *global solar radiation* (3.2.7).

3.2.9 *pyranometer*—see Terminology E 772.

3.2.10 *pyranometer, field*—a pyranometer essentially meeting WMO Second Class or better (that is, First Class) appropriate to field use and typically exposed continuously.

3.2.11 *pyranometer, reference*—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*—see Terminology E 772 and ISO 9060.

3.2.13 *pyrheliometer, absolute (self-calibrating)*—a solar radiometer in a pyrheliometer configuration having a field of view of approximately 5° and a slope angle of from 0.75 to 0.8°, and possessing 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*—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 with the cone formed between the origin of the receiver and the disk representing a subtendence of the sun that closely matches the field of view of the pyrheliometer against which it is compared. Alternatively, and increasingly preferred, is the use of a sphere rather than a disk; use of a sphere eliminates the need to continuously ensure the proper alignment of the disk normal to the sun.

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, 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 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 Fist Class pyranometers, or better, generally exhibit tilt errors of less than 1 % to tilts of 50° from the horizontal.

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] Available from American National Standards Institute, 11 W. 42nd St., 13th Floor, New York, NY 10036.

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

4.5.1 One of the International Pyrheliometric Comparisons held in Davos, Switzerland in either 1990 (IPC VII) or 1995 (IPC VIII).

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 circuity (neglecting cosine errors).

5. Selection of Shade Method

5.1 *Alternating Shade Method*:

5.1.1 The alternating shade method is required for a primordial 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. The voltage values from the pyranometer that correspond to direct solar irradiance are derived from the difference between the measured values of hemispherical solar irradiance and the diffuse solar irradiance. These values are measured periodically by means of a movable sun shade disk. For the calculation of the responsivity, the difference in the components of irradiance is divided by the measured direct solar irradiance 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 X1.

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 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 E 842.

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, and the diffuse solar irradiance measured with a shaded reference pyranometer.

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 by the component summation (continuous shade) method. 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 The 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 The disadvantage of the component-summation method is the complexity of the apparatus to effect a continuously moving, that is, tracking, shaded disk with respect to the reference pyranometer's receiver.

5.3.3 The 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 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 *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 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° of the sun during the period that data are taken for record.

6.2 *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 pyranometer with the cable connection mounted downward. When calibrating a pyranometer with its axis vertical, the sun angle changes through a range of azimuths. Hence, the azimuthal angle between the sun and the direction of the cable connector or other reference mark may be significant.

6.3 *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.

6.3.1 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 along the pyranometer axis. 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.

6.3.2 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 are small in most applications and essentially can be ignored.

6.3.3 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.

6.4 *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.

6.5 *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 3—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.

6.5.1 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.

6.5.2 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.

6.6 *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 sunlight onto the calibration facility. When calibrating at tilt angles from the horizontal, the foreground shall be selected so as not reflect sunlight onto the test facility from materials, objects or the ground (for example, snow, sand, etc.).

6.6.1 During calibration, wind conditions are also important, since absolute cavity pyrheliometers operating with open tubes are 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 and 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 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.

7.5 *Primary Standard Pyrheliometer*—A self-calibrating absolute cavity pyrheliometer designated by the WMO Guide and ISO 9060 as a primary standard, and intended for use in Type I calibrations.

NOTE 4—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 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 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 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 should be larger than the radius of the outer glass dome of the pyranometer by a minimum of $d \tan(0.5°)$ to allow for the divergence of the sun's beam and for small tracking errors.

7.8.1.3 The ratio r/d 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 5—All pyrheliometers listed in Footnotes [5] and [7] possess slope angles of approximately 1° and field-of-views between 5 and 6°.

NOTE 6—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 X2, 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[7]. 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. This approach is currently under investigation in the United States.

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

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 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.

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

[6] The sole source of supply of the solar tracker is SCI-TEC, Saskatoon, Canada. 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.

[7] Zerlaut, G. A., *Solar Radiation Instrumentation, Solar Resources*, ed. R. Hulstrom, The MIT Press, Cambridge, MA. 1989.

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 alternating with n intervals during which the pyranometer is unshaded and exposed to hemispherical solar radiation.

NOTE 7—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 Class 1 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.

10.2.3 Record the following values in accordance with Fig. 1: diffuse solar radiation $E_{D,\beta}$ 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 $E_{G,\beta}$ measured at the end of each even numbered exposed (illuminated) interval nt_o for n intervals; direct solar radiation E_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.

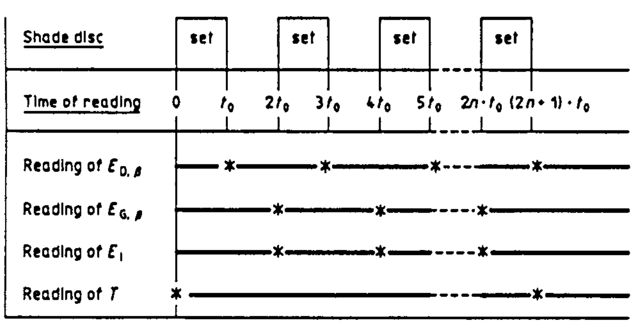

FIG. 1 Measurement Sequence for the Alternating Sun-and-Shade Method Using Equal Timing Intervals

10.2.4 Record the time of each measurement required in 10.2.3 precisely in order to accurately calculate the solar incidence angles (see 12.1-12.4).

10.2.5 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.

10.3 *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:

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

and:

$$\bar{R}_S = \frac{\sum_{i=1}^{n}\{V_{G,\beta}(2i) - 0.5[V_{D,\beta}(2i-1) + V_{D,\beta}(2i+1)]\}}{\sum_{i=1}^{n} V_I(2i)F_P\cos[\eta(2i)]} \quad (3)$$

where:

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;