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Solar energy — Calibration of a pyranometer using a pyrheliometer

Énergie solaire — Étalonnage d'un pyranomètre utilisant un pyrhéliomètre

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Contents

Annexes

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 9846 was prepared by Technical Committee ISO/TC 180, *Solar energy*, Sub-Committee SC 1, *Climate – Measurement and data*.

Annexes A, B, C, D, E, F and G of this International Standard are for information only.

Introduction

This International Standard is one of a series of standards specifying methods and instruments for the measurement of solar radiation.

From meteorological applications of pyranometers, considerable experience has been gained with a number of calibration methods. These methods may be divided into two groups specified by the type of reference radiometer used. Calibration methods using pyranometers as a reference have been treated in ISO 9847; methods using pyrheliometers are the subject of this standard.

The latter methods are more complicated than the former, because the pyranometers, which typically have a field-of-view angle of 2π, have to be compared with pyrheliometers, which are designed to measure direct solar radiation within a relatively small field of view.

On the other hand, due to the relatively high accuracy of pyrheliometers, the latter methods are more accurate than the former ones. Since the WMO world radiometric reference (WRR), which represents the SI units of irradiance, is determined by a group of selected pyrheliometers, the transfer of the scale to pyranometers has to be accomplished by using standard pyrheliometers (see ISO 9060). Short descriptions of the calibrations are given in [1], [2] and [3].

It should be emphasized that "calibration of a pyranometer" essentially means the transfer of the WRR scale to the pyranometer under selected conditions. The determination of the dependence of the calibration factor (calibration function) on variable parameters is called "characterization". The characterization of pyranometers is the subject of the appropriate International Standard for test methods for pyranometers.

Solar energy — Calibration of a pyranometer using a pyrheliometer

1 Scope

The object of this International Standard is to promote the uniform application of reliable methods to calibrate pyranometers, since accurate calibration factors are the basis of accurate hemispherical solar radiation data which are needed for solar energy test applications or simulations.

This International Standard is applicable to all pyranometers in horizontal as well as in tilted positions. Its use is mandatory for the calibration of secondary standard pyranometers according to ISO 9060, and is recommended for the calibration of pyranometers which are used as reference instruments in comparisons. For other applications, the method using pyranometers as references may be used (see ISO 9847).

This International Standard is intended for use by test institutions or test laboratories equipped with well-maintained pyrheliometers.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 9060:1990, *Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation.*

ISO 9847:1992, *Solar energy — Calibration of field pyranometers by comparison to a reference pyranometer.*

ISO/TR 9901:1990, *Solar energy — Field pyranometers — Recommended practice for use.*

3 Definitions

For the purposes of this International Standard, the definitions given in ISO 9060 and the following definitions apply.

3.1 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 reference pyranometer: Pyranometer (see ISO 9060), used as a reference to calibrate other pyranometers (see ISO 9847), which is a well-maintained and carefully selected instrument of relatively high stability and which has been calibrated using a pyrheliometer.

3.3 field-of-view angle of a pyrheliometer: Full angle of the cone which is defined by the centre of the receiver surface (see ISO 9060, 5.1) and the border of the aperture, if the latter is circular and concentric to the receiver surface; if not, effective angles may be calculated [4].

3.4 solar tracker; sun tracker: Power-driven or manually operated support which is employed to direct a pyrheliometer to the sun.

"Equatorial trackers" are sun-following devices which have an axis of rotation pointing towards the elevated pole; the axes of motion are the hour angle and the declination of the sun. "Altazimuth trackers" are sun-following devices with the solar elevation angle and the azimuth angle of the sun as coordinates of movement.

3.5 sun-shading disc device; shade disc device: Device which allows movement of a disc in such a way that the receiver of the radiometer (for example, a pyranometer) is shaded from the sun.

For calibration purposes, particularly those described in clause 5, quick removal of the disc is mandatory. Further details on shade disc devices used in calibrating pyranometers are given in 5.2.4.

3.6 direct solar radiation: That part of the extraterrestrial solar radiation which as a collimated beam reaches the earth's surface after selective attenuation by the atmosphere.

The quantity measured is the direct solar irradiance, expressed in watts per square metre (see also ISO 9060).

3.7 hemispherical solar radiation; global radiation: Combined direct solar radiation and diffuse solar radiation.

The quantity measured is the hemispheric solar irradiance, expressed in watts per square metre (see also ISO 9060).

3.8 diffuse solar radiation: That part of solar radiation which reaches the earth as a result of being scattered by the air molecules, aerosol particles, cloud and other particles.

The quantity measured is the diffuse solar irradiance, expressed in watts per square metre (see also ISO 9060).

NOTE 1 For meteorological purposes, the solid angle from which the scattered radiative fluxes are measured shall be the total sky hemisphere, excluding a small solid angle around the sun's disc.

4 Selection of methods

Two calibration methods have been selected for standardization, because they are widely used and are reliable. Both methods use shade disc devices for measuring diffuse solar radiation and are based on the hemispherical solar radiation being equal to the sum of direct solar and diffuse solar radiations.

The derived calibration factors are representative of cloudless or scattered cloud conditions (see clause 8 for uncertainties). A modification of the calibration method in clause 5 for application during less stable sky conditions is briefly described in annex C.

Annex D contains a short description of an extended version of the calibration method in clause 6 to determine the dependence of the calibration factors on incidence angles.

5 Alternating sun-and-shade method

5.1 Principle

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 (see note 1, 3.8). These values are measured periodically by means of a movable sun shade disc. For the calculation of the responsivity, the difference in irradiance components is divided by the measured direct solar irradiance normal to the receiver plane of the pyranometer.

In the following subclauses the basic method is described. Modifications of this method, which may improve the accuracy of the calibration factors but require more operational experience, are mentioned in annexes C and D.

5.2 Apparatus

5.2.1 Pyranometer.

In principle, this method can be applied to any type of pyranometer.

5.2.2 Pyrheliometer.

The choice of pyrheliometer used as the reference should be made according to the required accuracy and the operational conditions. Generally, secondary standard or first class instruments (see classification in ISO 9060) which are regularly compared with primary standards represent a satisfactory level of accuracy (see also clause 8). The pyrheliometer should produce at least one reference value every 2 min.

5.2.3 Solar tracker, power driven or manually operated, employed to direct the reference pyrheliometer to the sun for the entire test period. A solar tracker of the altazimuth type should be used for pyrheliometers whose responsivity over the receiver surface is not circular-symmetrical. The required tracking accuracy depends on the slope angle (see ISO 9060) of the pyrheliometer. In the usual case the slope angle is about 1°.

5.2.4 Shade disc device, meeting the following requirements:

a) The shade disc shall be positioned perpendicular to the sun's ray and at a fixed distance d from the centre of the receiver surface of the pyranometer.

b) The radius r of the shade disc 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 beam and small tracking errors.

c) The ratio r/d should define an angle at the centre of the receiver surface which corresponds to the field-of-view angle of the pyrheliometer.

NOTE 2 A fixed "shade slope angle", corresponding to the slope angle of the pyrheliometer, can only be stated for pyranometers which are operated in a position normal to the sun's ray. For other pyranometers, the shade slope angle varies according to the angle of incidence of the ray on the receiver plane.

d) Those parts of the disc holder which 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 0,5 %. Similar regard to interference with other neighbouring instruments should be considered.

e) The shade disc must be easy to remove and replace, so that the change from the shade phase to the hemispheric solar irradiance phase, or vice versa, takes less than 5 % of the phase duration.

The five types of shade disc devices briefly described in annex A are the designs of different institutions; only one of them is commercially available at present.

5.2.5 Data acquisition system.

To acquire the values, in millivolts, of the radiometer readings, the system should be equipped with a precise digital voltmeter with a resolution of 1 µV and an uncertainty of 0,1 % of the pyranometer's calculated output at 1 100 W m^{-2}. 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 period, the data should be appropriately recorded.

5.3 Measurement conditions

Clear sky conditions are essential for reduced variance in the results. However, clouds are tolerable if they are at a large angular distance from the sun (> 45°) and have a low angular velocity, to guarantee stable values of diffuse solar radiation within the cycle time of the measurement procedure (see 5.7.1); i.e. the change in the diffuse solar irradiance must be negligible. In the case of tilted pyranometers, clouds which are outside the field of view have minimal influence on the measurement procedure.

In principle, the other environmental conditions during calibration should be similar to the typical conditions during normal use of the pyranometer. The most important parameter is the range of solar elevation, followed by the ambient air temperature, level of hemispherical solar irradiance and tilt angle.

During calibration, wind conditions are also important, since pyrheliometers operating with open tubes are disturbed by strong wind speeds, especially gusts coming from the sun's azimuthal direction. It is recommended that pyrheliometers are operated with wind screens if wind-induced instability of the measurements is intolerable.

5.4 Measurement site

The measurement site shall offer rigid supports to install the instruments and be of convenient access.

In the case of horizontal pyranometers, obstructions on the horizon are tolerable provided they do not obscure the sun during the calibration period and their effect on the measurements varies monotonically at a small rate (see 5.7.1). Specular reflection by obstructions should be avoided. In the case of inclined pyranometers, signal contributions from the radiation reflected by the foreground should vary in the sense mentioned above.

Space must be provided around the pyranometers for the movement of the shade disc. The distance to other instruments should be large enough so that possible interference can be neglected.

The distance between the pyrheliometer and the pyranometer should be less than 30 m, otherwise both radiometers may not be similarly affected by the same atmospheric events (for example, structured turbidity elements).

5.5 Installation

The installation of the pyrheliometer and the solar tracker as well as the pyranometer with the shade disc device shall be carried out as described in the appropriate operation and manufacturer's manuals, and considering 5.4.

Pyranometers which are used in combination with a ventilation device should also be ventilated during the calibration procedure.

In the case of inclined pyranometers, the cable outlets should point downwards to avoid interference from rain or direct solar radiation (see ISO/TR 9901).

5.6 Calibration procedure

5.6.1 Preparatory phase

Start the preparatory phase about 30 min before the measurement phase to allow for:

- acclimatization of the radiometers, electronics and data acquisition system;
- adjustment of radiometers, solar tracker and shade disc device;
- checking of the electrical connections, test voltages and zeroing tests;
- final cleaning of the optical windows.

5.6.2 Measurement phase (single series)

The measurement phase consists of $(2n + 1)$ intervals. During $(n + 1)$ intervals the pyranometer is shaded; during n intervals, which alternate with the former, the pyranometer is exposed to hemispheric solar radiation.

During the measurement phase

a) the pyranometer, tilted at an angle β, indicates:

- if shaded, the signal for diffuse solar irradiance $E_{D,\beta}$ (including reflected solar irradiance if $\beta \neq 0$), $(n + 1)$ values. Read at the end of each shading interval t_0 (see graph below)
- if exposed to hemispheric solar radiation, the signal for hemispherical solar irradiance $E_{G,\beta}$, n values. Read at the end of each exposure to hemispherical solar radiation interval t_0 (see graph below);

b) the pyrheliometer indicates the signal for direct normal solar irradiance E_I, n values. Read simultaneously with $E_{G,\beta}$ (see graph below);

c) the thermometer indicates ambient air temperature or radiometer temperature T, with readings at least at the start and the end of the series.

The time interval of each phase t_0 corresponds to the time interval within which the pyranometer signal achieves its assumed final value. Set (or remove) the shade disc immediately (see 5.2.4) after the readings of $E_{G,\beta}$ (or $E_{D,\beta}$) have been taken.

The measurement sequence is illustrated in the following scheme:

where t_0 is that time interval or response time in which the pyranometer signal achieves a final value deviating less than 0,3 % from the theoretical final value.

NOTE 3 The setting of the same time interval t_0 for the shading and hemispherical solar radiation phase is based on the assumption that the response time of the pyranometer during increasing and decreasing signals is approximately the same.

The choice of t_0 should consider the setting conditions during fine weather and cloudless conditions.

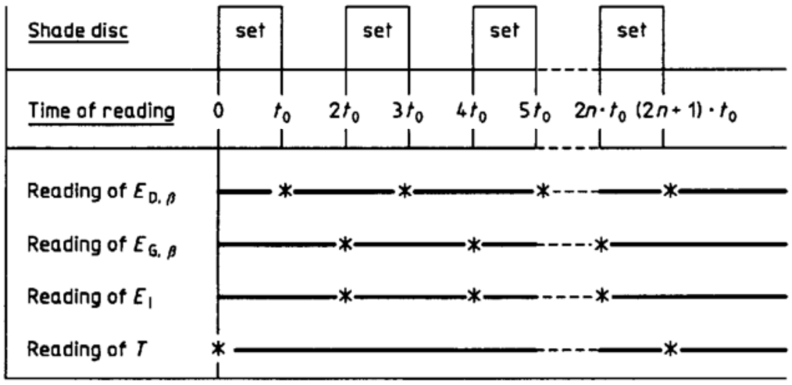
Generally, for commercially available pyranometers t_0 lies between 1 and 4 min; t_0 may be reduced by wind or the artificial ventilation of the instrument.

The time interval between readings of the radiometer may be up to about 20 % longer than the shortest estimate t_0 if the system is unstable (owing to gusts or dust clusters, for instance). In any case, the time of measurement must be recorded carefully for calculation of the solar incidence angles (see 5.2.5).

Restrict the number of intervals n of each series so that the duration $(2n + 1)t_0$ of a series is not longer than 36 min. The mean value of series of such duration can then be associated with small ranges of solar elevation and temperature. The number of intervals n shall not be less than 3.

5.6.3 Number of series

Since the results of each series can exhibit scatter, at least 10 series should be completed, from which the final result can be determined. Complete the series over three or more days to obtain enough series at mean solar incidence angles which deviate less than ± 5° from that angle representing the normal operating conditions.



5.7 Determination of the calibration factor

5.7.1 Evaluation of a single series

Determine the responsivity $R_S(i)$ and the mean responsivity $\overline{R}_S$, expressed as microvolts per watt per square metre or as millivolts per milliwatt per square centimetre, from the appropriate group of measurements according to:

$$R_S(i) = \\ = \frac{\{V_{G,\beta}(2i) - 0{,}5[V_{D,\beta}(2i-1) + V_{D,\beta}(2i+1)]\}}{\{V_I(2i)\cdot F_p\cdot \cos[\eta(2i)]\}} \quad \ldots (1)$$

$$\overline{R}_S = \\ = \frac{\sum_{i=1}^{n}\{V_{G,\beta}(2i) - 0{,}5[V_{D,\beta}(2i-1) + V_{D,\beta}(2i+1)]\}}{\sum_{i=1}^{n} V_I(2i)\cdot F_p\cdot \cos[\eta(2i)]} \quad \ldots (2)$$

where

i	indicates the measurement within the series;
S	indicates the series;
$V_{G,\beta}(2i)$	is the hemispherical solar irradiance signal measured at position $2i$ within the series, in millivolts, for instance;
$V_{D,\beta}(2i-1)$ or $V_{D,\beta}(2i+1)$	is the diffuse solar irradiance signal measured at position $(2i-1)$ or $(2i+1)$ within the series, in millivolts, for instance;
$V_I(2i)\cdot F_p$	is the direct solar irradiance calculated from the product of the pyrheliometer signal $V_I(2i)$ and its calibration factor F_p;
$\eta(2i)$	is the angle between the direction of the solar beam and the perpendicular to the receiver plane of the pyranometer, at the time corresponding to set position $2i$. The angle of incidence η is calculated (see annex B) from the inclined position of the pyranometer and the solar position;
n	is the number of readings of $E_{G,\beta}$ and E_I to be used from the total number of reading intervals $(2n+1)$.

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

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

$$R_S = \overline{R}_S(i, i = 1, n \text{ for } i \neq j) \quad \ldots (3)$$

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

5.7.2 Evaluation of the final results

If p calibration series are carried out at the desired parameter ranges, the final responsivity R is calculated as the mean of all responsivities R_S:

$$R = \frac{1}{p}\cdot\sum_{l=1}^{p} R_S(l) \quad \ldots (4)$$

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 $f(T,T_n)$ to each R_S according to:

$$R = \frac{1}{p}\cdot\sum_{l=1}^{p} f[T(l),T_n]\cdot R_S(l) \quad \ldots (5)$$

NOTE 4 For some types of pyranometers, temperature coefficients α are specified so that simply $f(T,T_n) = [1 - \alpha(T - T_n)]$ is applicable.

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

$$F = \frac{1}{R} \quad \ldots (6)$$

and the responsivity R.

6 Continuous sun-and-shade method

6.1 Principle

The pyranometer is compared with two reference radiometers, namely a pyrheliometer and a well-calibrated pyranometer measuring diffuse solar radiation. The hemispherical solar irradiance is determined by the sum of the direct solar irradiance and the diffuse solar irradiance. The direct solar irradiance is derived from the pyrheliometer signal. The diffuse solar irradiance is measured continuously by the second pyranometer with a shade disc device. The method can deliver continuous results if continuous pyrheliometer readings can be taken. The reference pyranometer is traceable to a pyranometer calibrated with the sun-and-shade method.

6.2 Apparatus

6.2.1 Pyranometer.

In principle this method can be applied to any type of pyranometer. Secondary standard or first class instruments which have to be calibrated regularly are recommended as reference pyranometers (see ISO 9060). Pyranometers recommended for measuring diffuse solar irradiance in clear sky conditions are those which have low directional errors, the smallest possible decrease in spectral responsivity in the ultraviolet region $> 0{,}3$ µm and a small diameter of the effective receiver surface compared with the diameter of the glass domes.

6.2.2 Pyrheliometer.

See 5.2.3, but well-calibrated pyrheliometers providing continuous signals are preferred.

6.2.3 Solar tracker.

See 5.2.3.

6.2.4 Shade disc device.

See 5.2.4, but without item e). Use of an automatic shade disc is recommended.

6.2.5 Data acquisition system.

See 5.2.5, but in the case of continuous data measurement, consideration should be given to reduce data acquisition to periods of up to 10 min.

6.3 Measurement conditions

In general, conditions as described in 5.3. Since the data can be acquired continuously, data obtained under cloudy conditions are also acceptable, as long as

— the angular distance of the clouds from the sun is greater than 15° and

— the angular velocity of clouds within the field of view of the pyranometer is small enough so that the diffuse solar irradiance varies less than 1 % in about 10 s.

6.4 Measurement site

In general, the measurement site should be as specified in 5.4. The test pyranometer shall be sufficiently separated from the vicinity of the shading disc device of the reference pyranometer to ensure that it is not influenced by the disc device. Additionally, any obstructions within the fields of view of the reference and test pyranometers must be nearly identical and, for inclined installations, the foregrounds must be nearly identical.

6.5 Installation

See 5.5, but the two pyranometers shall be installed in the same inclined position.

6.6 Calibration procedure

6.6.1 Preparatory phase

As described in 5.6.1. Take great care in determining the zero offsets of the radiometer signals.

6.6.2 Measurement phase (single series)

The measurement phase of each series consists of between 10 and 20 sets of readings (each measurement being completed within 1 s) of:

— hemispherical solar irradiance signal $V_{G,\beta}$ from the test pyranometer at the tilt angle β;

— diffuse solar irradiance signal $V_{D,\beta}$ from the reference pyranometer at the tilt angle β;

— direct solar irradiance signal V_I from the reference pyrheliometer.

Measure the temperature of the ambient air or of a radiometer body, as well as the irradiance zero, at the beginning and at the end of each series, and of each set.

Take the readings periodically if this is required by the operational mode of the pyrheliometer; if not, limit the timing of measurements to the most stable periods. However, take sets from all parts of the series so that the result is representative of the total period. Carefully record the time of each set for a subsequent calculation of the solar incidence angle.

Choose the sampling frequency depending on the operational mode of the pyrheliometer to be between 2 per minute and 0,5 per minute. The number of sets per series should be between 10 and 20, with the duration of a series between 10 min and 30 min.

NOTE 5 If the pyrheliometer is capable of measuring the direct solar irradiance continuously, the use of integrated values is possible. The integration interval should be no longer than 6 min or 2 min, in the case of clear or cloudy sky, respectively. Non-negligible uncertainties may be introduced in the calculation of R_S [equation (7)] by using the mean solar incidence angle η over the integration interval.

6.6.3 Number of series

Measure at least 10 series spread over at least three days. If the data are taken over less than three days, justification/documentation shall be provided.

6.7 Determination of the calibration factor

6.7.1 Evaluation of a single series

a) 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.

b) Calculate the mean responsivity R_S, expressed in microvolts per watt per square metre, from single readings of one measuring series:

$$R_S = \frac{\frac{1}{m} \cdot \sum\limits_{i=1/i \neq j}^{k} V_{G,\,\beta}(i)}{\sum\limits_{i=1/i \neq j}^{k} [V_I(i) \cdot F_p \cos \eta(i) + V_{D,\,\beta}(i) \cdot F_D]} \qquad \ldots (7)$$

where

i	indicates the position of a data set within the series;
k	is the total number of readings of each radiometric quantity = total number of data sets;
j	indicates the eliminated data sets within the series;
m	is the number of valid data sets;
$V_{G,\,\beta}(i)$	is the hemispherical solar irradiance signal measured by the instrument being calibrated, in millivolts, for instance;
$V_{D,\,\beta}(i)$	is the diffuse solar irradiance signal, including reflected solar irradiance if $\beta \neq 0$, measured at position i within the series, in millivolts, for instance;
F_D	is the diffuse irradiance calibration factor of the reference pyranometer;
$V_I(i)$	is the direct normal solar irradiance signal, measured at position i within the series, in millivolts, for instance;
$\eta(i)$	is the solar incidence angle between the direction of the sun's beam and the perpendicular to the receiver plane of the test pyranometer at the time of the reading of set i (see annex B);
F_p	is the calibration factor of the reference pyrheliometer;
$V_I(i) \cdot F_p \cdot \cos \eta(i)$	is the direct solar irradiance projected on the receiver plane of the pyranometer.

6.7.2 Evaluation of the final results

Evaluation is carried out as specified in 5.7.2.

7 Certificate of calibration

The certificate shall state as a minimum the following information on

a) the test pyranometer:

- manufacturer, type and serial number;
- position (inclination angles, azimuthal orientation and tracking);
- special remarks on the state of the instrument;

b) the reference instruments:

- manufacturer, type and serial number;
- hierarchy of traceability;
- shade disc geometry;
- corrections applied;

c) the procedure:

- type of procedure (i.e. reference to this International Standard);
- site (latitude, longitude and altitude);
- date and time of calibration;
- number of series;
- ranges of measurement parameters (solar elevation angle, hemispherical solar irradiance, turbidity and temperature);
- application of reduction formulae;

d) the result of the calibration:

- responsivity, expressed in microvolts per watt per square metre, and calibration factor, expressed in watt square metres per microvolt (final mean value R);

- standard deviation (of R_S related to R);
- range of validity (parameters: solar elevation angle, temperature, etc.).

8 Uncertainty

8.1 A basic uncertainty in the determination of the calibration factor is inherent in the use of the reference pyrheliometer. This uncertainty is caused initially by the transfer of SI units to the pyrheliometer, which amounts to about 0,7 % and 1,0 % for a secondary standard and a first class pyrheliometer, respectively; the values are increased to 0,9 % and 1,5 % because of the permissible range of instrument instability over two years (see ISO 9060).

NOTE 6 In the case of the continuous sun-and-shade method (see clause 6), a well-characterized reference pyranometer contributes to the uncertainty of the reference values of the hemispherical solar irradiance by less than 1 % if the sky is cloudless. Under cloudy conditions, the uncertainty is increased based on the increased amount of diffuse solar radiance in the global radiation.

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 disc geometry according to 5.2.4), readings and careful operation.

NOTE 7 As 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 of the projected direct solar irradiance [see equations (1), (2), (3) and (7)]. Therefore a 1 % uncertainty requires that the angles of incidence are restricted to less than 60°.

8.2 The sample standard deviation, calculated from the results of all series, is indicative of the variation in meteorological conditions (for example, wind), and instrument precision and variabilities (for example, azimuthal response of the pyranometer). Its amount depends on the tolerated ranges of the parameters.

8.3 Concerning the uncertainty, fundamental differences between the alternating and the continuous sun-and-shade methods do not exist. The former method delivers calibration factors which should be preferably applied when scattered cloud conditions are typical; the calibration factors determined with the latter method, supported by careful zeroing procedures and careful installation of both pyranometers for "seeing" the same horizon and foreground, are preferred in clear sky conditions. The calibration factor of the latter method may be higher by about 0,5 % depending on the reading of the theoretical final values (see 5.6.2).

A comparison of the advantages and disadvantages of the two methods is given in annex F.

Annex A
(informative)

Shade disc devices

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

a) a disc

- of a well-defined radius r [$\geqslant$ radius of pyranometer dome $+ d$ tan 0,5°; for d, see b)];
- painted black on the side opposite to the pyranometer;
- equipped with a means to fasten the disc to the support;

b) a disc support, designed to

- be as small as possible (to minimize additional shading of the pyranometer);
- be as rigid as possible (to avoid large disc movement caused by wind);
- allow movement of the disc for screening the sun;
- fix the distance d between the disc centre and the centre of the receiver for any position of the disc;

c) a mount, designed to

- bear the disc support;
- move the support, manually or by a motor, in order to keep the disc in the correct shading position;
- be fastened to the instrument platform or similar.

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

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

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

A.2.1 Shade disc device of a sun-tracking pyranometer (operated at normal incidence)

As shown in figure A.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.

A.2.2 Manually operated shade disc device for stationary pyranometers

a) Mount alongside the pyranometer

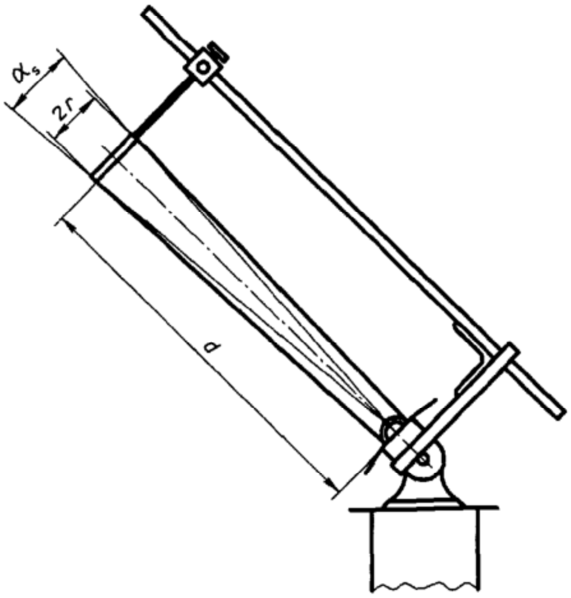
As shown in figure A.2, the mount is designed as a turnable rod standing upright on the polar side of the pyranometer. The rod supporting the disc is rotated horizontally to set the disc. (It is not feasible to set the disc at a constant distance to the receiver.)

b) Mount concentric to the pyranometer

As shown in figure A.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.

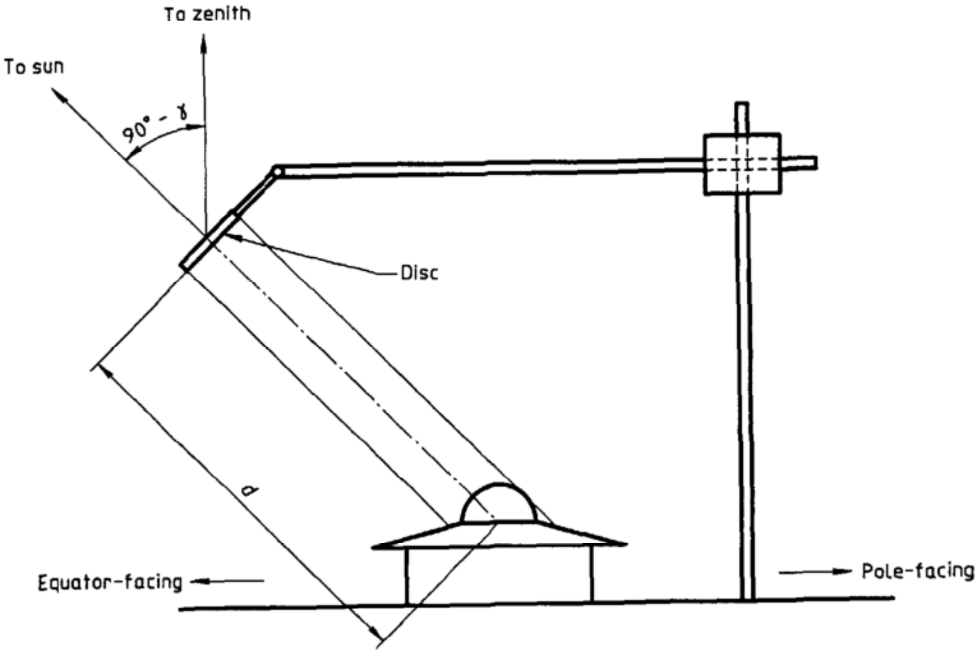
A.2.3 Semi-automatic motor-driven device for continuous shading

As shown in figure A.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.



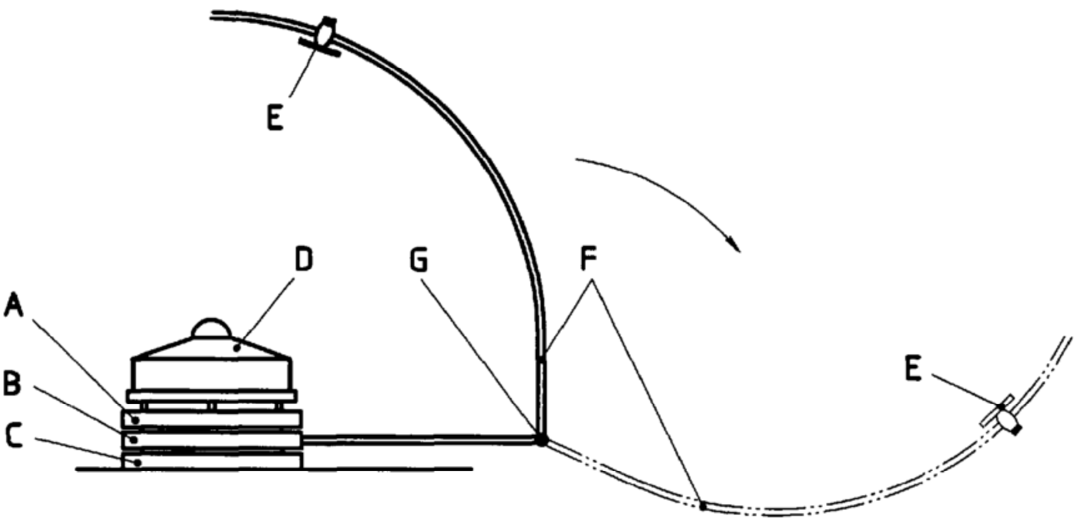
$\alpha_s = 2 \arctan r/d$

Figure A.1 — Shade disc device used with a sun-tracking pyranometer [5]



γ: Solar elevation angle

Figure A.2 — Shade disc device installed alongside the pyranometer [5]



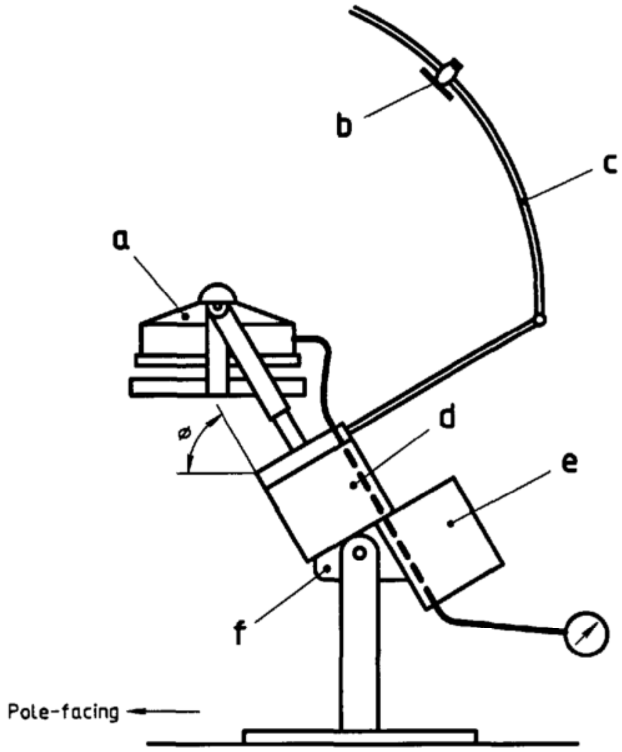
A: Rotatable plate for turning the pyranometer D separately

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

Figure A.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

Figure A.4 — Semi-automatic shade disc device

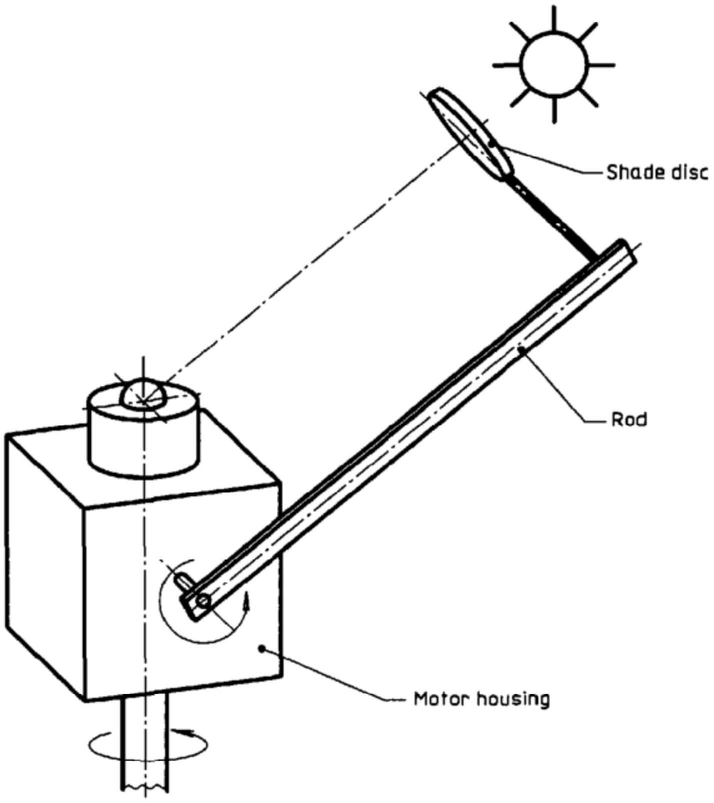
A.2.4 Fully automatic motor-driven device for continuous or alternating shading

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 figure A.5 a), illustrating a SCI-TEC[1] 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 figure A.5 b)]. Because of the computer control of the disc movement, the removal and the setting of the disc during the calibration process is easily programmable.

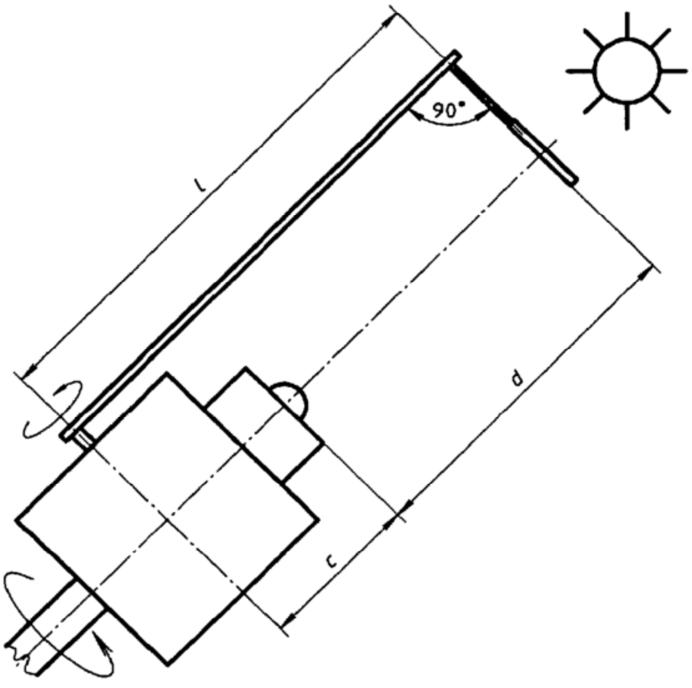
This device does not completely fulfil the requirements in 5.2.4 a), since the distance c between the receiver plane and the elevation axis is not zero.

---

[1] This solar tracker is a product supplied by SCI-TEC, Saskatoon, Canada. This information is given for the convenience of users of this International Standard and does not constitute an endorsement by ISO of the product named. Equivalent products may be used if they can be shown to lead to the same results.



a) Solar tracker with shade disc



b) Solar tracker in tilted position

Figure A.5 — Fully automatic shade disc tracker

Annex B
(informative)

Calculation of the angle of incidence η of a solar beam on an inclined plane

B.1 According to the formula of spherical geometry, $\cos\eta$ (see also figure B.1) is given by

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

where

γ	is the solar elevation angle;
ψ	is the solar azimuth angle, measured from south positive to west, negative to east;
β	is the tilt angle of the plane against the horizontal;
α	is the azimuth angle of the normal to the plane.

B.2 Using astronomical consideration, the abovementioned coordinates of the sun can be calculated from:

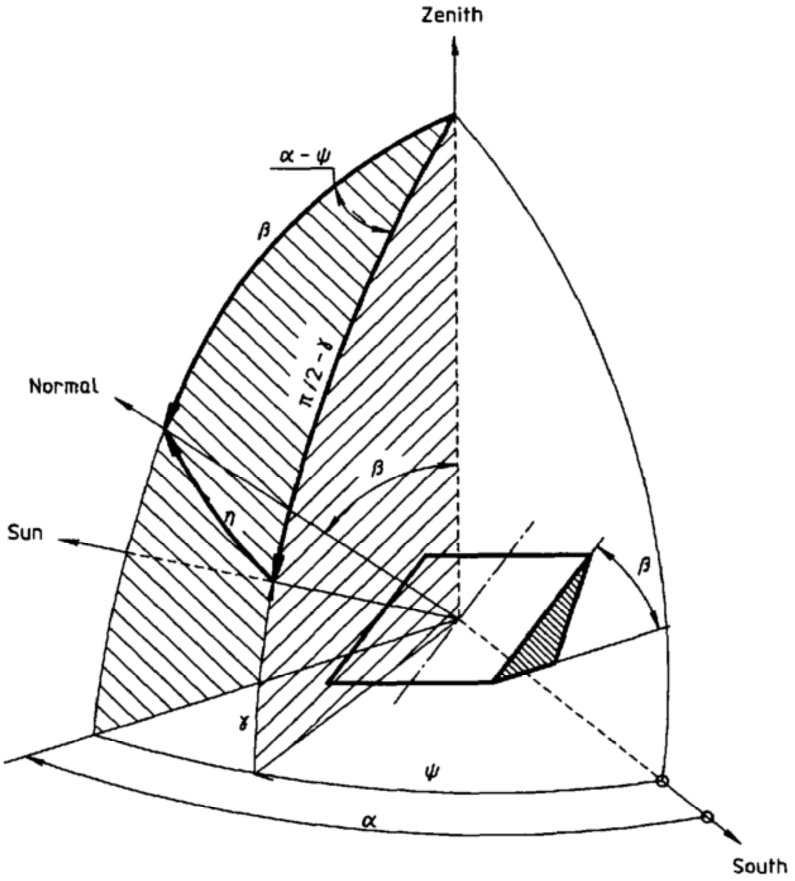
$$\sin\gamma = (\sin\phi \cdot \sin\delta) + (\cos\phi \cdot \cos\delta \cdot \cos\omega)$$

$$\cos\psi = \frac{(\sin\phi \cdot \sin\gamma) - \sin\delta}{\cos\phi \cdot \cos\gamma}$$

where

ϕ	is the geographical latitude of the point of observation;
δ	is the solar declination;
ω	is the solar hour angle (angle between the hour circle of the sun and the local meridian, at the time of observation).

For more detailed information see [6], for example.



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

Figure B.1 — Definition of the angle η between the direction of the sun and the normal to the tilted plane

Annex C

(informative)

Extended version of the sun-and-shade method

C.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).

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

C.2 $V_{\mathrm{D},\beta}(2i)$ (see 5.7.1) is obtained more accurately by reference to the signal from a continuously-shaded pyranometer $V_{\mathrm{D},\beta}^{\bullet}$:

$$V_{\mathrm{D},\beta}(2i) = \frac{k_1 + k_2}{2} \cdot V_{\mathrm{D},\beta}^{\bullet}(2i)$$

where

$$k_1 = V_{\mathrm{D},\beta}(2i-1)/V_{\mathrm{D},\beta}^{\bullet}(2i-1)$$

$$k_2 = V_{\mathrm{D},\beta}(2i+1)/V_{\mathrm{D},\beta}^{\bullet}(2i+1)$$

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

$V_{\mathrm{D},\beta}(2i)$ replaces the interpolation term $0{,}5[V_{\mathrm{D},\beta}(2i-1) + V_{\mathrm{D},\beta}(2i+1)]$ in the responsivity equations (1) and (2) (see 5.7.1).

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

Annex D
(informative)

Multiple-reading version of the alternating sun-and-shade method

D.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 10 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.

D.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.

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

a) Systematically take 10 readings within the last $0{,}15t_0$ seconds of each interval (the 10th reading corresponds to the single reading in the basic version, t_0 being the interval time).

b) Calculate the arithmetic mean value of the 10 readings.

c) Compare the 10 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.

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

e) Use this new mean value in the further calculations described in 5.6.3.

Annex E
(informative)

Extended version of the continuous sun-and-shade method

E.1 This extended version of the continuous sun-and-shade method allows the systematic determination of the dependence of the responsivity of the pyranometer being tested on the incidence angle.

E.2 The equipment is that required for the alternating sun-and-shade method. To derive the desired responsivity function of the test pyranometer, an iterative algorithm is used. In the basic equation, an estimate of the angular distribution of the sky radiance is introduced. It removes from the continuous sun-and-shade method result the biases due to diffuse irradiance, and can be used over a wide range of zenith distances. However, it requires measurements from either sunrise to solar noon, or solar noon to sunset, to be effective.

E.3 This method is described in references [7] and [8], annex G.

Annex F
(informative)

Comparison of the alternating sun-and-shade method (ASSM) and the continuous sun-and-shade method (CoSSM)

F.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.

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

a) 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.

b) 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 equation (1)].

c) 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.

d) 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 figure A.4.

e) 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.

f) 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 annex D.

g) 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.

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.

Annex G
(informative)

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Descriptors: solar energy, solar radiation, radiation measurement, radiation measuring instruments, pyranometer, calibration.

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