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Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation

Énergie solaire — Spécification et classification des instruments de mesurage du rayonnement solaire hémisphérique et direct

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Contents

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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 9060 was prepared by Technical Committee ISO/TC 180, *Solar energy*.

Annexes A, B and C of this International Standard are for information only.

Introduction

This International Standard is one of a series of standards that specify methods and instruments for the measurement of solar radiation in support of solar energy utilization.

Accurate solar radiation data are used in meteorology and are needed for developing solar energy appliances, in particular for performance testing, solar radiation simulation and resource assessment.

The measurement of radiation is needed for determination of the conversion efficiencies of solar appliances. The specification and classification of these instruments are needed in order to enable the comparison of solar radiation data on a worldwide basis.

The specification and classification of solar radiometers prescribed in this International Standard are based on a terminology and methodology that is similar to that used by the World Meteorological Organization (WMO). However, both the specification and the classification deviate from the WMO documents in order to meet the requirements specific to solar energy utilization and appliances.

In particular, this International Standard establishes the regulations necessary for the implementation of the classification.

Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation

1 Scope

This International Standard establishes a classification and specification of instruments for the measurement of hemispherical solar and direct solar radiation integrated over the spectral range from 0,3 µm to 3 µm.

Instruments for the measurement of hemispherical solar radiation and direct solar radiation are classified according to the results obtained from indoor or outdoor performance tests. Primary standards, which are direct solar radiation instruments, are classified on the basis of their design and specification of measuring reproducibility under outdoor test conditions verified by periodic pyrheliometric intercomparisons.

2 Normative reference

The following document contains provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the edition indicated was valid.

World Meteorological Organization, *Guide to Meteorological Instruments and Methods of Observation*, No. 8, 5th edition, WMO, Geneva, 1983.

3 Definitions

For the purposes of this International Standard, the following definitions apply.

3.1 hemispherical solar radiation: Solar radiation received by a plane surface from a solid angle of 2π sr.

NOTE 1 More than 99 % of the hemispherical solar radiation incident at the earth's surface is contained within the wavelength range from 0,3 µm to 3 µm. Generally, hemispherical solar radiation is composed of direct solar radiation and diffuse solar radiation (solar radiation scattered in the atmosphere) as well as solar radiation reflected by the ground.

3.2 global (solar) radiation: Hemispherical solar radiation received by a horizontal plane surface.

3.3 direct solar radiation: Radiation received from a small solid angle centred on the sun's disc, on a given plane.

NOTE 2 In general, direct solar radiation is measured by instruments with field-of-view angles of up to 15°. Therefore a part of the scattered radiation around the sun's disc (circumsolar radiation) is also included (see 5.1).

More than 99 % of the direct solar radiation received at the ground is contained within the wavelength range from 0,3 µm to 3 µm.

3.4 pyranometers: Radiometers designed for measuring the irradiance on a plane receiver surface which results from the radiant fluxes incident from the hemisphere above within the wavelength range 0,3 µm to 3 µm.

NOTE 3 The spectral range given is only nominal. Depending on the materials used for the domes which protect the receiving surface of a pyranometer (see 4.1), the spectral limits of its responsitivity approximate to the limits mentioned above.

Radiometers which are of design similar to pyranometers, but which are equipped with photoelectrical sensors having spectral responsivity which is not as uniform over the spectral range as required in table 1 (reference No. 3d), are often designated by the name of the sensor, for instance "Silicon-pyranometer" (or, for short, Si-pyranometer).

3.5 pyrheliometers: Radiometers designed for measuring the irradiance which results from the solar radiant flux from a well-defined solid angle the axis of which is perpendicular to the plane receiver surface.

NOTE 4 It follows from this definition that pyrheliometers are used to measure direct solar radiation at normal incidence. Typical field-of-view angles of pyrheliometers range from 5° to 10°. Unlike the windowless instruments, the spectral responsivity of field pyrheliometers is limited to the range approximately 0,3 µm to 3 µm, depending on the spectral transmittance of the window which protects the receiver surface. However, windowless instruments operate with a loss of energy of less than 1 % (see note 2 to 3.3).

3.6 world radiometric reference (WRR): Measurement standard representing the SI unit of irradiance with an uncertainty of less than ± 0,3 % (see the WMO *Guide to Meteorological Instruments and Methods of Observation,* 1983, subclause 9.1.3). The reference was adopted by the World Meteorological Organization (WMO) and has been in effect since 1 July 1980.

In order to ensure its long-term stability the WRR is realized by a group (known as the World Standard Group) of at least four pyrheliometers (see 5.2.1) of different design which are maintained by the WMO World Radiation Centre at Davos.

3.7 Linke turbidity factor: Relative measure of the attenuation of the direct solar radiation by the total atmosphere. It is related to the attenuation by molecule scattering only.

The Linke turbidity factor can be interpreted as an assumed multiplier of the path length through a clean non-absorbing molecular atmosphere to fit the measured beam attenuation. For the mathematical treatment, see [2].

4 Instruments to measure hemispherical solar radiation — Pyranometers

4.1 General physical design

Pyranometers are radiometers used to measure hemispherical solar radiation (see 3.1 and 3.4).

The spectral limits of the measurement only allow for thermal sensors, equipped with absorbing surfaces, to achieve the uniform spectral responsivity required for pyranometers (see table 1, reference No. 3d).

Thermal sensors transform radiant energy into thermal energy with a consequent rise in the temperature of the receiving surface. This rise in temperature is balanced by various kinds of heat losses to thermal sinks (e.g. the body of the pyranometer and ambient air).

The thermal sensor of a pyranometer is protected from wind, rain and dust as well as the exchange of thermal radiation by one or two glass domes whose spectral transmittance confines the spectral range of responsivity to approximately 0,3 µm to 3 µm.

The main parts of a pyranometer are

a) the thermal sensor, the receiving surface of which is painted black or alternatively black and white,

b) the glass dome(s) (one or two), which cover(s) concentrically the receiving surface, and

c) the body, which is often shielded by a sunscreen, and used as a thermal reference.

4.2 Types

The commonest type of pyranometer is the "thermoelectric" pyranometer which is equipped with a thermopile (sometimes called a thermobattery) measuring the difference in temperature between the blackened receiving surface (active junctions) and the body (passive junctions). The position and number of the active and passive junctions are quite different in different pyranometer models. Generally these sensors are covered by two concentric glass domes to achieve a strong attenuation of the off-set generated by thermal radiation.

Of a special design are the "black-and-white pyranometers". Their passive junctions are thermally connected to white segments which are regularly distributed over the relatively large receiving surface. Generally, only one dome is used in black-and-white instruments on the assumption that the thermal radiation is also absorbed equally by the white paint.

Pyranometers that are self-checking by means of electrical substitution of the radiant power are now commercially available. However, "absolute pyranometers" with cavity receivers (corresponding to "absolute pyrheliometers", see 5.2.1) are not yet on the market.

Radiometers with a 2π field-of-view angle based on photoelectric receivers (using silicon photovoltaic cells) are available as so-called "Si-pyranometers". Currently such instruments are not able to meet the uniformity of spectral responsivity as required for classification (see table 1).

Pyranometers of designs other than those described above may be used provided that they meet the specific requirements for solar energy applications. Detailed descriptions of various types of pyranometer are given in [1], [2] and [3].

4.3 Classification

The classification of pyranometers is based exclusively on the measuring specifications of the instruments according to their design and quality of manufacture.

NOTE 5 The accuracy of solar radiation data measured by pyranometers depends not only on the category of the instrument but also on

a) the calibration procedure,

b) the measurement conditions and maintenance, and

c) the environmental conditions.

Therefore statements about the overall measurement uncertainty can only be made on an individual basis, taking all relevant factors and the category of the instrument into account.

The classification scheme is based on various specifications, as given in table 1, and various classification criteria, as given in 4.3.2.

Three categories of pyranometer are defined as follows:

a) secondary standard pyranometer;

b) first class pyranometer (including the special group of first class pyranometer for solar energy test appliances);

c) second class pyranometer.

NOTE 6 A primary standard is not classified because the most accurate determination of global irradiance is believed to be the sum of the direct irradiance as measured by an absolute pyrheliometer and the diffuse solar irradiance as measured by a secondary standard pyranometer shaded from the sun by a disc.

4.3.1 Limiting values of pyranometer specifications

Pyranometer specifications can be grouped as follows:

a) the response time (a measure of the thermal inertia inherent in the stabilization period for a final reading);

b) the zero off-set (a measure of the stability of the zero-point specified for the effect of thermal radiation and for a temperature transient);

c) the dependence on responsivity resulting from

1) ageing effects (a measure of the long-term stability),

2) the level of irradiance (a measure of the non-linearity),

3) the direction of the irradiance (a measure of the deviations from the ideal "cosine behaviour" and its azimuthal variation),

4) the spectral distribution of irradiance (a measure of the spectral selectivity of responsivity),

5) the temperature of the pyranometer body, and

6) the tilt angle of the receiving surface.

A specification is fulfilled if the mean value of the respective test result does not exceed the corresponding limiting value of the specification given in table 1 for the specific category of instrument.

The specifications given in table 1 shall be verified by tests. Additional information on the specification items is given in annex A .

NOTES

7 Table 1 was developed on the basis of the corresponding WMO classification (see clause 2) which also defines three categories of pyranometer, i.e. secondary standard, first class pyranometer and second class pyranometer. The limiting values given in table 1 are in some cases more stringent than those given in the corresponding WMO table owing to the requirements of solar energy test applications and to recent improvements in measurement techniques.

8 The "first class pyranometer for solar energy test application" is defined in 4.3.2.

9 An International Standard dealing with methods for testing pyranometer characteristics is in preparation.

A pyranometer belongs to a specific category if all eight specifications (table 1) of the respective category are met and if the classification is in conformity with the criteria given in 4.3.2 and 4.3.3.

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Table 1 — Pyranometer specification list

Reference No.	Specification	Pyranometer category secondary standard	first class	second class
1	Response time: time for 95 % response	< 15 s	< 30 s	< 60 s
2	Zero off-set: a) response to 200 $W \cdot m^{-2}$ net thermal radiation (ventilated) b) response to 5 $K \cdot h^{-1}$ change in ambient temperature	+ 7 $W \cdot m^{-2}$ ± 2 $W \cdot m^{-2}$	+ 15 $W \cdot m^{-2}$ ± 4 $W \cdot m^{-2}$	+ 30 $W \cdot m^{-2}$ ± 8 $W \cdot m^{-2}$
3a	Non-stability: percentage change in responsivity per year	± 0,8 %	± 1,5 %	± 3 %
3b	Non-linearity: percentage deviation from the responsivity at 500 $W \cdot m^{-2}$ due to the change in irradiance within 100 $W \cdot m^{-2}$ to 1 000 $W \cdot m^{-2}$	± 0,5 %	± 1 %	± 3 %
3c	Directional response (for beam radiation): the range of errors caused by assuming that the normal incidence responsivity is valid for all directions when measuring from any direction a beam radiation whose normal incidence irradiance is 1 000 $W \cdot m^{-2}$	± 10 $W \cdot m^{-2}$	± 20 $W \cdot m^{-2}$	± 30 $W \cdot m^{-2}$
3d	Spectral selectivity: percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within 0,35 µm and 1,5 µm	± 3 %	± 5 %	± 10 %
3e	Temperature response: percentage deviation due to change in ambient temperature within an interval of 50 K	2 %	4 %	8 %
3f	Tilt response: percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1 000 $W \cdot m^{-2}$ irradiance	± 0,5 %	± 2 %	± 5 %

4.3.2 Classification criteria

The classification of pyranometers may be applied to individual instruments or to groups (particular types) of instruments, depending on the category.

A classification as **secondary standard pyranometer** may only be applied to an individual instrument if it complies with all the respective specifications given in table 1.

A classification as **first** or **second class pyranometer** may be obtained either for an individual instrument or for a particular type of pyranometer (instruments identical in design) that meets the respective specifications. A type of pyranometer may be claimed to be of a particular category if the appropriate category quality control has verified that every pyranometer complies with the respective specifications.

Pyranometers may be classified as **first class pyranometers for purposes of solar energy test applications** if the specifications for azimuthal and cosine response, first class instruments, given in table 1 are met for the individual instrument.

4.3.3 Identification of classification

The classification of a particular pyranometer shall be indicated by appropriate labelling of the instrument and by a test certificate provided by the issuing laboratory. The issuing test laboratory should be authorized by ISO.

5 Instruments to measure direct solar radiation — Pyrheliometers

5.1 General physical design

The main parts of a pyrheliometer are as follows:

a) the thermal sensor, the plane receiving surface of which is painted black or has a cavity to absorb the incoming radiation;

b) the view-limiting tube (or diaphragm tube, also called a sky-occluding tube), which defines the field-of-view geometry {the length l of the tube, the radius r_a of the aperture and the radius r_r of the receiving surface determine the central field-of-view angle $2 \arctan(r_a/l)$ and the slope angle $\arctan[(r_a - r_r)/l]$};

c) the adjustable mount, which causes the pyrheliometer to follow the sun or permits it to be adjusted to do so. (The adjustable mount can be an integral part by design of the instrument or a separate device to allow individual combination with an appropriate sun-following system.)

To restrict the requirements on both the accuracy of the sun-following device and the length of the tube to practical limits, the slope angles of commercially available pyrheliometers are of the order of 1°, and the field-of-view angles are about 5° for pyrheliometers of newer design and up to about 15° for those of older design.

Because the sun's disc has a diameter of 32′ as seen from the Earth, a larger amount of the aureole, depending on the content of atmospheric aerosol, is included in the measurements of direct solar radiation (see 3.3).

The receiving surface of pyrheliometers used for continuous field measurements is protected against dirt, insects, wind and other weather phenomena by a quartz window or a ventilation system.

Detailed descriptions of the various types of pyrheliometer are given in [1], [2] and [3].

5.2 Types

5.2.1 Absolute pyrheliometer

Principally an absolute pyrheliometer is a realization of the scale of irradiance.

NOTE 10 It is necessary to subject such an instrument to a close examination of its properties by means of laboratory measurements and model calculations to determine its deviation from ideal behaviour. This procedure is called the "characterization" of the instrument and yields a reduction factor which is used to transform the output signals to irradiances. The uncertainty in this factor determines the absolute accuracy of the instrument.

Absolute pyrheliometers of modern design use cavities as receivers and electrically calibrated differential heat-flux meters as sensors. They are operated in either "active" or "passive" mode. In the active mode the heat flux is maintained constant during both the shaded and the irradiated phase; the difference in electrical power during both phases is proportional to the radiative power. In the passive mode the electrical heating is maintained only during the shaded phase. In practice, when the pyrheliometer is in the active mode the radiation measurements will be interrupted periodically during the shaded phases of the measuring series, while in the passive mode the shaded phase occurs before the measuring series.

5.2.2 Compensation pyrheliometer

Pyrheliometers of older design (i.e. those without a cavity) which also have electrical substitution of the incident radiative power are still in common use in many national and regional radiation centres. These instruments have to be calibrated.

The Angström-Compensation-Pyrheliometer, for example, is equipped with two adjacent receivers, in one tube, which function alternately; one receiver is irradiated by the sun whilst the other is simultaneously shaded and electrically heated. This means that during the shading phase of one receiver, the measured radiation value of the other can be obtained.

5.2.3 Pyrheliometers without electrical substitution

These pyrheliometers are "relative instruments" and usually have thermopiles as detectors. They permit continuous recording of radiation and are used as field instruments; in most cases they are provided with a weather-proof enclosure.

5.3 Classification

Pyrheliometers are classified into two groups as follows:

a) primary standard pyrheliometer;

b) pyrheliometers of lower category.

Only absolute pyrheliometers, whose level of inaccuracy is essentially defined by the determination of its calibration factor and its long-term stability, may be classified as primary standards.

5.3.1 Primary standard pyrheliometer

5.3.1.1 An absolute pyrheliometer in accordance with the WMO specification for a primary standard instrument (see clause 2 and annex B) may be designated as a primary standard for the purposes of this International Standard.

5.3.1.2 Any absolute pyrheliometer may be designated as a primary standard for the purposes of this International Standard if it has been submitted to a "recognized pyrheliometer comparison" (see below) every 2 years over a period of 4 years and has been determined to function within 0,25 % of the reference.

For the purposes of this International Standard, a recognized pyrheliometer comparison shall comply with the following criteria.

a) The reference shall be established by at least two primary standards, one of which shall be submitted periodically to the WMO International Pyrheliometer Comparison.

b) The meteorological conditions during the comparison shall comply with the following specifications: sky conditions, cloudless; Linke turbidity factor, less than 5; wind speeds at the instrument site, less than 3 $m \cdot s^{-1}$; air temperature, greater than 0 °C.

c) The data acquisition system shall have a 5×10^{-5} resolution of 1 000 $W \cdot m^{-2}$ and should allow for an evaluation of comparison results between measuring series.

The classification of an absolute pyrheliometer as a primary standard shall be verified periodically in recognized pyrheliometer comparisons by testing that its responsivity remains within 0,2 % over a period of 2 years.

The historical records of the instrument performance and of its use in comparisons should be made available on request.

5.3.2 Pyrheliometers of lower category

Secondary standard pyrheliometers as well as first class and second class pyrheliometers are classified on the basis of the measuring specifications of the instruments (according to their design and quality of manufacture) and by regulation of the traceability to the scale.

NOTE 11 The accuracy of solar radiation data measured by pyrheliometers depends not only on the class of the instrument but also on the maintenance and the environmental conditions. Therefore, statements on the overall measurement uncertainty can only be made on an individual basis, taking into account all relevant factors and the category of the instrument.

Pyrheliometer specifications are given in table 2. The specifications are essentially the same as those used for pyranometers (see 4.3.1) except that the "directional response" is excluded and the "traceability" is included.

A specification is fulfilled if the mean value of the respective test result does not exceed the corresponding limiting value of the specification given in table 2 for the specific category of instrument.

A pyrheliometer belongs to a specific category if all eight specifications (table 2) of the respective category are met and if the classification is in conformity with the criteria given in 5.4.

5.4 Classification criteria

The classification of pyrheliometers may be applied to individual instruments or to groups (particular types) of instruments, depending on the category.

A **primary** or **secondary standard instrument** may only be designated as such on an individual basis.

A classification as **first** or **second class instrument** may be obtained either for individual pyrheliometers or for particular types of pyrheliometers (identical in design) that meet the respective specifications. Possible degradation and drift in performance shall be controlled by calibration to verify the classification as first and second class pyrheliometers. A type of instrument may be claimed to be of a particular category if the appropriate quality control has verified that every pyrheliometer complies with the respective specifications.

6 Final remarks

In addition to the classification and specification criteria specified in this International Standard, attention should also be paid to the following points to ensure that instruments achieve adequate accuracy in solar radiation measurement: proper adjustment, regular maintenance and the use of recording devices with sufficient sensitivity and stability.

Table 2 — Pyrheliometer specification list

Reference No.	Specification	Pyrheliometer category secondary standard	first class	second class
1	Response time: for 95 % response	< 15 s	< 20 s	< 30 s
2	Zero off-set: response to 5 $K \cdot h^{-1}$ change in ambient temperature	± 1 $W \cdot m^{-2}$	± 3 $W \cdot m^{-2}$	± 6 $W \cdot m^{-2}$
3a	Non-stability: percentage change in responsivity per year	± 0,5 %	± 1 %	± 2 %
3b	Non-linearity: percentage deviation from the responsivity at 500 $W \cdot m^{-2}$ due to the change in irradiance within 100 $W \cdot m^{-2}$ to 1 000 $W \cdot m^{-2}$	± 0,2 %	± 0,5 %	± 2 %
3d	Spectral selectivity: percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within 0,35 μm and 1,5 μm	± 0,5 %	± 1 %	± 5 %
3e	Temperature response: percentage deviation due to change in ambient temperature within an interval of 50 K	± 1 %	± 2 %	± 10 %
3f	Tilt response: percentage deviation from the responsivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1 000 $W \cdot m^{-2}$ irradiance	± 0,2 %	± 0,5 %	± 2 %
4	Traceability: maintained by periodic comparison	with a primary standard pyrheliometer	with a secondary standard pyrheliometer or better	with a first class pyrheliometer or better

Annex A
(informative)

Comments on the specifications given in table 1

NOTE 12 These comments are intended to highlight the reasoning for the choice of test parameters rather than to describe the details of the test methods (see note 9 to 4.3.1).

A.1 Response time

Owing to the fact that in general the thermal balancing process of pyranometers can only be described by several time constants, the settling behaviour should be characterized by the time during which the instrument reaches 95 % of the final value. The value given by the WMO is 99 %, which is closer to the final value but has a greater uncertainty owing to the off-sets and is more dependent on wind speed. However, it should be emphasized that for accurate measurement of the irradiance of rapidly changing radiation sources, even the time taken for 99,5 % of the value should be considered.

A.2 Zero off-set

The effects (producing zero off-set) mentioned are only the two most frequent cases. The case of rapid changes in body temperature, possibly effected by cold rain showers, is excluded.

It is acceptable for blowers to be used to meet the given upper limit values. For this case the blower, including the mechanical interface, must be commercially available and specified according to the parts to be ventilated and the cooling required.

For instance, the specified net thermal radiant flux density of 200 W·m^{-2} is realized when, at a body temperature of 30 °C, the sky temperature is −10 °C.

The specified change in body temperature per hour may occur during the morning of a fine day.

A.3 Non-stability

Generally, the reproducibility in testing the responsivity of the pyranometer is already within ± 0,5 %. Low stability of the pyranometer responsivity can be compensated for by more frequent recalibrations in accordance with the level of tolerable uncertainty.

A.4 Non-linearity

It is important that the non-linearity is specified for the total range of useful irradiances (approximately 100 W·m^{-2} to 1 000 W·m^{-2}).

A.5 Directional response (for beam radiation)

A.5.1 To ensure that the limiting values are met, measurement must be made of the responsivity relative to normal incidence at the following directions: incidence angles of 30°, 40°, 50°, 60°, 70° and 80° at 12 azimuth angles (0°, 30°, 60°, ..., 330°). (The azimuth angle $\psi = 0°$ represents the direction of the cable outlet of the pyranometer.)

A.5.2 The directionality of a pyranometer is characterized by the responsivity for beam radiation as a function of the direction of the radiation relative to the pyranometer. For an ideal pyranometer, the responsivity, which is the ratio of the signal to the incident irradiance, is independent of direction. The variation in responsivity with direction in real pyranometers causes measurement errors. These occur when either the responsivity variation or the angular distribution of the incident radiation or both are either unknown or ignored.

In table 1, reference No. 3c, the directionality is specified as an absolute error (in watts per square metre) that would be caused by ignoring the responsivity variation and using the value appropriate for normal incidence when measuring beam radiation whose normal incidence irradiance is 1 000 W·m^{-2}.

The mathematical expression for this "1 000 W·m^{-2} directional error" is

$$\Delta_{1000}(\theta, \psi) = 1000 \cos\theta \left[\frac{R(\theta, \psi)}{R(\theta = 0)} - 1 \right]$$

where

$\Delta_{1000}(\theta, \psi)$ is the 1 000 W·m^{-2} directional error, in watts per square metre;

θ is the incidence angle ($\theta = 0$ is normal incidence), in degrees;

ψ is the azimuth angle as in A.5.1, in degrees;

$R(\theta, \psi)$ is the responsivity to beam radiation at the direction specified θ, ψ, in watts per square metre;

$R(\theta = 0)$ is the normal incidence responsivity, in watts per square metre.

Another description of the directionality of a pyranometer, known as the "cosine error" or $\delta_{cos}(\theta, \psi)$, is often used. It is defined as the percentage deviation of the responsivity from the normal incidence value:

$$\Delta_{1000}(\theta, \psi) = 100\left[\frac{R(\theta, \psi)}{R(\theta = 0)} - 1\right]$$

The "cosine error" is related to the "1000 W·m^{-2} directional error" by

$$\delta_{cos}(\theta, \psi) = \frac{\Delta_{1000}(\theta, \psi)}{10 \cos \theta}$$

Laboratory measurements of directionality are invariably made by subjecting the pyranometer to beam radiation of constant power while varying the direction of the beam relative to the pyranometer. The signal $S(\theta, \psi)$ is recorded as a function of the direction. The "1000 W·m^{-2} directional error" and the "cosine error" are then calculated from the signals according to

$$\Delta_{1000}(\theta, \psi) = 1000\left[\frac{S(\theta, \psi)}{S(\theta = 0)} - \cos \theta\right]$$

and

$$\delta_{cos}(\theta, \psi) = 100\left[\frac{S(\theta, \psi)}{S(\theta = 0) \cos \theta} - 1\right]$$

where $S(\theta, \psi)$ is the signal, in volts.

Δ_{1000} has been chosen to specify the pyranometer classes in table 1 because it has a number of advantages over δ_{cos}, including that

a) it is a slowly varying function of direction,

b) it can be measured with approximately the same precision (≈3 W·m^{-2}) at all incidence directions, and

c) only one value for each pyranometer class is needed to specify the performance over all directions (i.e. 10 W·m^{-2}, 20 W·m^{-2} or 30 W·m^{-2}).

In addition, since the direct solar beam is never much more than 1000 W·m^{-2}, Δ_{1000} gives an approximate maximum limit to the error that might occur in ordinary outdoor usage owing to the directionality of the pyranometer response.

A.6 Spectral selectivity

The direct measurement of the spectral selectivity of a pyranometer would require a special highly sensitive measuring technique. The limits of the wavelength range given have been determined using Schott glass types WG 295 and K5. If the radiation of incandescent lamps is applied, the range greater than 1,5 µm shall also be considered.

A.7 Temperature response

The indication of the temperature interval of 50 K allows uniform classification of pyranometers for various climates.

A.8 Tilt response

The tilt response shall be determined under the most critical conditions, i.e. the most unfavourable azimuth position of the pyranometer with the use of an irradiance level of 1000 W·m^{-2}.

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Annex B
(informative)

Excerpt from the WMO *Guide to Meteorological Instruments and Methods of Observation,* subclause 9.3.1.1 (primary standard pyrheliometers)

"The following specification should be fulfilled by an absolute pyrheliometer before it can be designated and used as a primary standard:

a) At least one instrument out of a series of manufactured radiometers has to be fully characterized. The root mean square uncertainty of this characterization should be less than $\pm$ 0.25 %, referred to a full scale value of 1 kW·m^{-2}. The absolute uncertainty (simple addition of all individual uncertainties) should not exceed $\pm$ 0.5 %;

b) Each individual instrument of the series must be compared with the one which has been characterized, and no individual instrument should deviate from this instrument by more than the root mean square uncertainty determined under (a);

c) A detailed description of the results of such comparisons and of the characterization of the instrument should be made available upon request;

d) Traceability of the WRR by comparison with the World Standard Group or some carefully established and recognized equivalent is needed to prove that the design is within the state of the art. The latter is fulfilled if the WRR lies within the root mean square uncertainty as determined by (a)."

Annex C
(informative)

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