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Solar energy — Calibration of pyranometers by comparison to a reference pyranometer

Énergie solaire — Étalonnage des pyranomètres par comparaison à un pyranomètre de référence

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Contents

Page

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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 180, *Solar energy*, Subcommittee SC 1, *Climate – Measurement and data*.

This second edition cancels and replaces the first edition (ISO 9847:1992) which has been technically revised.

The main changes are as follows:

— focus on current calibration practices;

— adapted recommendations for mathematical treatment of data;

— adaptation of the terminology to the revised ISO 9060:2018 and ISO Guide 99[1];

— added comments on uncertainty evaluation of the calibration with reference to ASTM G213[2] and ISO/IEC Guide 98-3;

— inclusion of reference to non-spectrally-flat pyranometers, that are now also included in ISO 9060.

Annexes A, B, C, D, E and F are given for information only.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Pyranometers are instruments used to measure the irradiance (power per unit area) received from the sun for many purposes.

In recent years the application of hemispherical solar radiation measurement, using pyranometers, has risen sharply. The main application of pyranometers now is no longer scientific research, but assessment of the performance of solar power plants.

Accurate measurements of the hemispherical solar radiation are required for

a) the determination of the energy input to solar energy systems such as photovoltaic (PV) -, and solar thermal systems, as a basis for performance assessment,

b) the testing and assessment of solar technologies,

c) the geographic mapping of solar energy resources, and

d) other applications such as agriculture, building efficiency, material degradation and reliability, climate, weather, health, etc.

Today's growing solar energy performance assessment markets demand the lowest possible measurement uncertainties. To meet this demand, a measurement requires an uncertainty evaluation and an accurate time stamp[3].

Calibration of measuring instruments is an essential part of the uncertainty evaluation and part of any quality management system. Regular instrument re-calibration according to this standard helps attaining the required low measurement uncertainties. Calibration usually will show the instrument is stable and then serves as:

— confirmation that the measurement data collected over the time interval from the previous to the present calibration are reliable

— the instrument is expected to remain stable, future measurement data are expected to be reliable.

Uncertainties mentioned in this document are expanded uncertainties with a coverage factor $k = 2$.

Solar energy — Calibration of pyranometers by comparison to a reference pyranometer

1 Scope

This document specifies two preferred methods for the calibration of pyranometers using reference pyranometers; indoor (Type A) and outdoor (Type B).

Indoor or type A calibration, is performed against a lamp source, while the outdoor method B, employs natural solar radiation as the source.

Indoor calibration is performed either at normal incidence (type A1), the receiver surface perpendicular to the beam of the lamp or under exposure to a uniform diffuse lamp source using an integrating sphere (type A2).

Outdoor calibration is performed using the sun as a source, with the pyranometer in a horizontal position (type B1), in a tilted position (type B2), or at normal incidence (type B3).

Calibrations according to the specified methods will be traceable to SI, through the world radiometric reference (WRR), provided that traceable reference instruments are used.

This document is applicable to most types of pyranometers regardless of the type technology employed. The methods have been validated for pyranometers that comply with the requirements for classes A, B and C of ISO 9060. In general, all pyranometers may be calibrated by using the described methods, provided that a proper uncertainty evaluation is performed.

Unlike spectrally flat pyranometers, non-spectrally flat pyranometers might have a spectral response that varies strongly with the wavelength even within the spectral range from 300 to 1 500 nm, and therefore the calibration result may possibly be valid under a more limited range of conditions.

The result of a calibration is an instrument sensitivity accompanied by an uncertainty. This document offers suggestions for uncertainty evaluation in the annexes.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
pyranometer
radiometer 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.

[SOURCE: ISO 9060:2018, 3.5, modified — Tolerances have been changed and the Note 1 to entry was deleted.]

3.2
hemispherical solar radiation
solar radiation received by a plane surface from a solid angle of 2π sr

[SOURCE: ISO 9060:2018, 3.1, modified — Note 1 to entry was deleted.]

3.3
global horizontal solar irradiance
GHI
G
hemispherical solar radiation received by a horizontal plane surface

[SOURCE: ISO 9060:2018, 3.2, modified — Symbol *G* and abbreviation GHI were added and Note 1 to entry was deleted.]

3.4
sensitivity
quotient of the change in an indication of a measuring system and the corresponding change in a value of a quantity being measured

Note 1 to entry: See Reference [1].

3.5
calibration of a pyranometer
determination of the relationship between the *pyranometer* (3.1) output and the irradiance, with associated measurement uncertainties, under well-defined operating conditions

Note 1 to entry: For most pyranometers, the output varies linearly with the irradiance and the calibration result is expressed as a single sensitivity.

Note 2 to entry: See References [1] and [4].

3.6
reference pyranometer
pyranometer (3.1) used as reference standard, i.e. an instrument used for calibration of other pyranometers in a given organization

3.7
test pyranometer
pyranometer (3.1) being calibrated

Note 1 to entry: Called field pyranometer in the previous version of this document.

3.8
calibration conditions
conditions, ambient- or instrument, during the calibration process

3.9
reference-operating condition
operating condition prescribed for evaluating the performance of a measuring instrument or measuring system or for comparison of measurement results

Note 1 to entry: For practical purposes these typically are the conditions specified for the reported sensitivity.

Note 2 to entry: For measurement results, see Reference [1].

3.10
world radiometric reference
WRR
measurement standard representing the SI unit of irradiance with an uncertainty of less than ±0,3 %

Note 1 to entry: The reference was adopted by the World Meteorological Organization (WMO) and has been in effect since 1 July 1980. The WRR is maintained by the WMO World Radiation Centre at Davos. The distinguishing feature of traceability to WRR is that reference-operating conditions include the spectrum of natural direct solar radiation.

3.11
sample
data acquired from a sensor or measuring device

Note 1 to entry: See Reference [5].

3.12
sampling interval
time between *samples* (3.11)

Note 1 to entry: See Reference [5].

3.13
record
data recorded and stored in data log, based on acquired *samples* (3.11)

Note 1 to entry: See Reference [5].

3.14
data series
set of selected *records* (3.13)

3.15
correction
value added algebraically to the uncorrected result of a measurement to compensate for systematic error

[SOURCE: ISO Guide 98-3:2008, B.2.23]

Note 1 to entry: The correction for offsets is equal to the negative of the estimated systematic error. Since the systematic error cannot be known perfectly, the compensation cannot be complete.

3.16
correction factor
numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error

Note 1 to entry: Since the systematic error cannot be known perfectly, the compensation cannot be complete.

[SOURCE: ISO Guide 98-3:2008, B.2.24]

3.17
solar tracker
mechanical device capable of rotation around 2 axes, e.g. zenith and azimuth, following the path of the sun

3.18
integrating sphere
sphere or hemisphere, equipped with one or more lamps, internally coated with a spectrally flat white paint providing uniform illumination

3.19
tilt angle
angle between the horizontal plane and the plane of the *pyranometer* (3.1) sensor surface

3.20
angle of incidence
angle of radiation relative to the sensor measured from normal incidence (varies from 0° to 90°)

3.21
zenith angle
angle of incidence (3.20) of radiation, relative to zenith (angle between the earth's surface normal and the line to the sun)

Note 1 to entry: It equals the *angle of incidence* (3.20) for horizontally mounted instruments.

3.22
solar azimuth angle
angle between a reference direction (north or south) and the projection of beam radiation on the horizontal plane

Note 1 to entry: Duffie and Beckman[6] define the reference direction (zero solar azimuth angle) as south for both the northern and southern hemisphere. In the Duffie and Beckman definition the azimuth angle ranges from −180° to +180°, where angles east of south are negative and west of south positive. Other references and models use north as reference direction.

4 Pyranometer calibration

4.1 General

Calibration of a pyranometer involves a test to determine the relationship between pyranometer output and irradiance. The result is usually expressed as a single sensitivity, with associated uncertainty, under well-defined operating conditions. Pyranometer calibration may be carried out according to ISO 9846[4], outdoors against a pyrheliometer, or according to this document, indoors or outdoors against a reference pyranometer. Both documents describe how to transfer the sensitivity of the reference instrument to the test instrument.

The recommended calibration interval for pyranometers differs from one manufacturer to the other. IEC 61724-1[5] recommends instrument recalibration once every 2 years or more frequently according to manufacturer recommendations for Class A monitoring systems, and according to manufacturer recommendations for Class B systems. For Class A monitoring systems for global horizontal solar irradiance and plane of array irradiance measurement, this document requires a calibration uncertainty of less or equal than 2 %. Under typical but not all conditions, this uncertainty is attainable with pyranometers having calibration uncertainties in the order of 1,5 % or better[3].

4.2 Pyranometer sensitivity, measurement equation, measurand

The relationship between pyranometer sensitivity, output and irradiance or measurement equation for thermal pyranometers is given by Formula (1):

$$S = V/G \tag{1}$$

where

S	is the sensitivity in output units/(W/m^2);
G	is the global horizontal solar irradiance in W/m^2;
V	is the pyranometer output in arbitrary units.

Calibration of pyranometers essentially consists of a measurement at or traceable to an irradiance level in the middle or close to the upper end of the measurement range.

Clear sky conditions are the most common calibration reference condition for calibration, so that during calibration the measurand formally is global horizontal solar irradiance under a clear sky.

NOTE Calibration reference conditions can differ from the operation conditions in several ways, not only spectrally, but can also differ in terms of e.g. temperature, wind, solar position, atmospheric conditions (cloud cover, aerosols) and instrument tilt. Even the measurand can change (calibrated for global irradiance, used for diffuse or reflected irradiance measurements). If the calibration reference conditions and the operating conditions are different the user considers this for the uncertainty evaluation of the measurements and considers proper corrections.

While traditional pyranometers had analogue millivolt output signals, many modern pyranometers have different, for example digital or current-loop, outputs. These are often standardised outputs. The calibration process of these instruments typically includes adjustment by programming a new sensitivity into the firmware, so that the sensitivity after calibration as perceived by the user is always the same; for example, 1 $(W/m^2)/(W/m^2)$ for digital instruments or 0 W/m^2 = 4 mA, 1 600 W/m^2 = 20 mA for a pyranometer with a current-loop output. For these instruments the measurement Formula (1) is adapted accordingly.

The calibration of instruments with standardised outputs is nevertheless expressed in $V/(W/m^2)$ because this gives a clear indication of the correction applied from one calibration to the next, and of the stability of the sensor. For instruments with such internal signal conversion, the voltage measurement usually is not separately calibrated. In such cases the $V/(W/m^2)$ shall be interpreted as $V/(W/m^2)$ “as measured by the on-board analogue to digital conversion”.

In exceptional cases laboratories and users may choose to use alternative measurement equations. They may use a correction factor acting on in S, for example accounting for temperature dependence.

ISO 9060 defines the measurement error "zero offset A". Corrections for zero offset A can be made during outdoor calibration. It may lead a higher accuracy of the calibration. However, care should be taken to ensure that the same correction technique used in calibration is then used for subsequent measurements. The zero offset A is not constant. It depends on the environmental conditions for example on cloud condition, sky temperature, wind speed (ventilator application), and thermal coupling of the instrument to its mounting. Applying such corrections may lead to a lower measurement accuracy.

When applying corrections for offsets, the measurement Formula (1) then gets the form of Formula (2):

$$S = (V - V_0)/G \tag{2}$$

where

S is the sensitivity in output units/(W/m^2);

G is the irradiance in W/m^2;

V is the pyranometer output in arbitrary units;

V_0 is an offset on the output in arbitrary units.

Working with instruments calibrated with a correction for offsets according to Formula (2), users shall also adapt their measurement equation from Formulae (1) and (2).

Additional corrections for example for temperature dependence, and outdoor solar- or indoor lamp spectrum can also be implemented.

Annex C contains informative comment on what to do with calibration results; how to introduce a new pyranometer sensitivity.

4.3 Indoor and outdoor calibration compared

Under this document, there are two options for pyranometer calibration: indoors, in the laboratory using lamps as a source and outdoors under the Sun. There are the following fundamental differences:

— An indoor calibration is only the transfer of the outdoor calibration of the reference instrument to a test instrument.

— Indoor calibration is done by comparison of the test pyranometer to a reference pyranometer of the same model, and thus of the same class. Initial (i.e. before making optional corrections) reference-operating conditions, the condition for which the calibration of the test instrument is valid, are the conditions reported as valid for the calibration of the reference pyranometer.

— Outdoor calibration is done by comparison of the test pyranometer to the reference pyranometer, where the reference pyranometer is not necessarily of the same model, typically of a higher or equal class. Initial reference operating conditions are the outdoor conditions during this calibration.

— For both indoor and outdoor calibration, the reference-operating conditions may later, in the calibration report, be adapted to other conditions than those to which the calibration is initially traceable. This then leads to an adapted sensitivity and reduces the calibration accuracy.

In all cases corrections shall also be accounted for in the calibration uncertainty and be reported on the calibration certificate.

Calibration laboratories may report multiple sensitivities valid for different reference-operating conditions, so that users may work with a sensitivity valid for conditions as close as possible to actual operating conditions (e.g. sensitivities for a non-spectrally flat pyranometer operating under clear and overcast sky conditions).

The uncertainty evaluation for one instrument may be used for other instruments of the same model as long as the conditions of testing remain the same and the method for evaluation is verified (the identified critical influencing factors are under control). Some laboratories use statistical data of the test or multiple tests as input to the uncertainty evaluation. In that case calibration of the same pyranometer model may have a variable uncertainty.

For outdoor calibration, the conditions of testing (temperature, angle of incidence/airmass) usually vary between one calibration and the next and the uncertainty of the calibration result (sensitivity) will typically vary. For indoor calibration the conditions of testing can be kept within certain known limits and the contribution to the uncertainty can be constant.

4.4 Method validation

The methods described in this document have been validated for pyranometers that comply with the requirements for classes Spectrally Flat A, B and C of ISO 9060 and silicon photodiode pyranometers complying with class C.

For new instrument designs, possibly working according to new measurement principles, the methods may equally be applicable, but this shall be proven by testing for the individual instrument design.

4.5 Calibration uncertainty

Laboratories shall perform an uncertainty evaluation of all their calibrations and supply this evaluation with the calibration in summary. Uncertainty evaluations shall be made according to ISO/IEC Guide 98-3, and express uncertainties as expanded measurement uncertainties with a coverage factor of 2 (confidence level typically representing approximately 95 % of the data points, and two standard deviations).

The calibration uncertainty for indoor calibration depends on

— calibration method,

— pyranometer type, and

— uncertainty of the sensitivity of the reference pyranometer.

The uncertainty of indoor calibration may be based on a limited set of tests involving the pyranometer type and the method, and calculations according to ISO/IEC Guide 98-3. It may then be treated as a constant percentage of the sensitivity.

The uncertainty of outdoor calibrations depends on above factors and also on

— solar angle of incidence,

— instrument temperature, and

— atmospheric stability.

The uncertainty of outdoor calibration may not be based on a limited set of tests involving the pyranometer type. Because of the variability of the environmental factors, the uncertainty shall be analysed separately for every individual calibration. Typically, calibration conditions and uncertainty will not be the same from one calibration to the other.

NOTE Pyranometer calibration uncertainties are relatively large, while the expected instrument drift from one calibration to the next is typically small compared to the uncertainty of calibration. It is therefore often more probable that perceived sensitivity changes are caused by differences associated with calibration methods (even for application of the same method between different laboratories) or reference pyranometers used, rather than by the non-stability of the calibrated pyranometer. This situation is exceptional. In most other areas of metrology, the uncertainty of calibration is not a limiting factor; in these other areas it is possible to calibrate with an uncertainty lower than the 1 % (expanded $k = 2$) that is attainable with pyranometers. Both for ISO 9846 and for the procedures described in this document the uncertainties contributed by the calibration method are in the order of 0,5 % when performed with care, where the uncertainty using the calibration using a pyrheliometer is lower than that with a pyranometer. Combined with other uncertainties such as those of the reference pyranometer sensitivity and the WRR scale, these lead to calibration uncertainties of commercially available Class A instruments in the order of 1,5 %. See Annex F and References [17] to [19] for examples.

For spectrally non-flat pyranometers the influence of the calibration conditions on the measurement uncertainty is high compared to spectrally flat pyranometers. This shall be considered when selecting the calibration duration, the number of days used, and the conditions observed during the calibration. The closer the calibration conditions match the conditions during the operation of the test pyranometer the lower the measurement uncertainty in the application. For example, an instrument calibrated under a clear sky may be used under overcasts skies, using a correction applied on the sensitivity. This correction will have its own uncertainty.

NOTE Using the sensitivity of a silicon photodiode pyranometers obtained from a calibration under clear sky conditions under overcast sky condition may lead to a 8 % or more overestimation of the solar radiation[7].

5 Measuring equipment

5.1 Data acquisition and recording

Traditionally pyranometers were passive instruments with an analogue output in the millivolt range. Nowadays pyranometers may also have other outputs such as an amplified voltage, a current loop or a digital signal. Laboratories should select the data acquisition based on their own requirements. When using pyranometers with an analogue (as opposed to digital) output, the measurement specifications of the data acquisition system are an important factor influencing the calibration accuracy. Their contribution to the uncertainty should be no more than 0,1 %.

5.2 Instrument platforms

A platform for mounting instruments is required for all horizontal, B1 type, and tilted, B2 type, calibrations. In case it is tilted, it shall be able to be tilted over a suitable range of angles from the horizontal with an uncertainty of less than 0,5°.

Pyranometers have to be accurately aligned; the deviation between the tilt angle of the reference pyranometer and that of the test pyranometer shall be not more than 0,2°. An alignment error of more than 0,1° may have an impact on the calibration result, depending on solar zenith angle.

5.3 Pyranometers

Pyranometers shall be in clean and in good condition.

The test pyranometer should not show signs of degradation; check that the colour of the black absorber paint or white diffuser has not changed by comparing to a reference pyranometer of the same type. There should not be signs of corrosion on the connector pins.

The pyranometer bubble levels should be high-quality and stable. Typically, this is verified by visual observation, and possibly by mounting on a level plate.

The reference and test pyranometers shall be internally dry. This is verified, for example by looking at the colour of the humidity indicator or the output of internal humidity sensors. If humidity indicators are absent this may be verified by looking for any signs of condensation inside the dome. Humidity may also condense in the dome during outdoor measurement.

6 Indoor calibration (Type A)

6.1 Introductory remarks on indoor calibration

Indoor calibration is carried out in a controlled laboratory environment using a lamp as a source.

Indoor transfer of the sensitivity of a calibrated reference pyranometer may only be carried under the condition that the calibration reference pyranometer is of the same model as the test pyranometer. The calibration may then be carried out using a lamp as a source which has a different emission spectrum than that of the sun, and at a relatively low irradiance level (typically in the range of 300 W/m^2 to 1 000 W/m^2).

The reference pyranometer will typically be calibrated outdoors according to ISO 9846[4].

Since the test and reference pyranometer are of the same model, both instruments will respond in the same way when irradiance level, tilt error and spectrum deviate from the conditions during outdoor calibration (i.e. the linearity and spectral response of both instruments are identical, therefore these effects will cancel). This way, the newly calibrated test instrument will obtain a sensitivity that is valid under the same outdoor reference conditions of irradiance, tilt and spectrum under which the reference pyranometer was calibrated. The additional step of the indoor transfer calibration only leads to a small increase of the calibration uncertainty, it does not change the reference conditions of the calibration.

For example, in case the reference pyranometer has been calibrated under clear sky conditions (the radiation spectrum is not specifically defined) over a range of 500 W/m^2 to 1 000 W/m^2, the sensitivity of the newly calibrated pyranometer will also be valid for an irradiance range of 500 W/m^2 to 1 000 W/m^2 and for the clear sky conditions.

6.2 Reference pyranometers for indoor calibration

The reference pyranometer for indoor calibration (type A) shall be of the same model as the test pyranometer. The same model is understood as having the same optics and thermal and detector design, but not necessarily as having the same model name.

6.3 Indoor calibration systems

6.3.1 System with a direct beam source (type A1)

Type A1 calibration requires a lamp source, possibly combined with optical apertures and lenses creating a stable and spatially uniform beam on one or more pyranometers. The system has positioners or a translating- or rotating mechanism to accurately exchange instrument positions or exchange instruments at one single position. The system has an optical shutter so that unshaded (light) and shaded (dark) records can be taken. The apparatus is placed in a dark room or contains a dark measurement compartment to mitigate the influence of the environment.

Annex A gives examples of possible designs of such systems.

6.3.2 Systems with an integrating sphere source (type A2)

For calibration type A2, an integrating sphere or hemisphere is required, offering a near perfect homogeneous and diffuse source over the full field of view of the pyranometers. The system may have positioners or a translating or rotating mechanism to accurately exchange instrument positions or exchange instruments at one single position. Alternatively, the system may be designed such that the pyranometers are positioned symmetrically so all have a homogeneous and identical field of view of the source and no positional exchange is required as part of the calibration procedure. The user may make an unexposed (dark conditions, zero irradiance) measurement and correct for zero offsets.

Annex A gives one example of a possible design of such a system.

6.4 Indoor calibration procedures

6.4.1 Calibration procedure requirements (types A1 and A2)

Calibration requirements for indoor calibration are:

— reference and test pyranometer shall be mounted in the same plane, having the same detector height;

— exact exchange of the positions between reference and test pyranometer should be possible;

— the difference between irradiance levels at the instrument positions should be as small as possible but shall be lower than 10 %;

— records used for calibration should be based on samples taken after more than 3 × the 95 % response time as specified for the pyranometer type in ISO 9060, has elapsed.

6.4.2 Indoor calibration procedures (types A1 and A2)

Check that the reference and test pyranometers are of the same model.

Allow electronics and the lamp to stabilize. A stability- check is built into the mathematical treatment of 6.4.3.

Properly position the pyranometers under the lamp or integrating sphere source. Optionally, determine zero offsets, and compensate for these, for example by taking records of the output of the pyranometers alternately shaded and unshaded. For instruments that do not suffer from zero offsets, such as pyranometers equipped with photodiode sensors, the zero offset measurement does not need to be done. Optionally, exchange instrument positions to compensate for inhomogeneity of the irradiance.

If fast-response (photodiode) pyranometers are used, the detector will not (like most thermal pyranometers) average over several cycles of the mains power. This means - depending on the light source used - it may be sensitive to power oscillations. Note that the power frequency is two times the voltage frequency. Therefore, the sampling frequency should be a multiple of 100 Hz and 120 Hz for mains frequencies of 50 Hz and 60 Hz respectively. Alternatively, an integrated value over the full oscillation period should be recorded.

Apply the mathematical treatment described in 6.4.3.

6.4.3 Calculation of the sensitivity

Calculate the measured values, V, from the records taken using the following Formulae (3) to (6):

$$V_{\mathrm{r}} = V_{\mathrm{r,u}} - V_{\mathrm{r,s}} \tag{3}$$

$$V_{\mathrm{t}} = V_{\mathrm{t,u}} - V_{\mathrm{t,s}} \tag{4}$$

$$V_{\mathrm{r}}' = V_{\mathrm{r,u}}' - V_{\mathrm{r,s}}' \tag{5}$$

$$V_{\mathrm{t}}' = V_{\mathrm{t,u}}' - V_{\mathrm{t,s}}' \tag{6}$$

where

V	is the pyranometer output in arbitrary units;
r	is the reference pyranometer;
t	is the test pyranometer;
u	is the unshaded (light);
s	is the shaded (dark) offset or zero offset obtained in another way;
ʻ	are the records taken with sensor positions exchanged at a new moment in time (or in case only 1 instrument mounting location is available: the repeat reference and test samples obtained at the same position at different times).

Verify that the lamp source is stable by checking whether the condition

$$(1-k) < \frac{V_{\mathrm{r}} V_{\mathrm{t}}'}{V_{\mathrm{r}}' V_{\mathrm{t}}} < (1+k) \tag{7}$$

is fulfilled, for $k \leq 0{,}01$.

Calibration laboratories may also use a smaller value of k than 0,01, which is beneficial for the calibration uncertainty.

If the condition is fulfilled, calculate the sensitivity, S_{t}, of the test pyranometer from:

$$S_{\mathrm{t}} = \frac{V_{\mathrm{t}} + V_{\mathrm{t}}'}{V_{\mathrm{r}} + V_{\mathrm{r}}'} S_{\mathrm{r}} \tag{8}$$

or from:

$$S_{\mathrm{t}} = \left(\frac{V_{\mathrm{t}}}{V_{\mathrm{r}}'} + \frac{V_{\mathrm{t}}'}{V_{\mathrm{r}}} \right) \frac{S_{\mathrm{r}}}{2} \tag{9}$$

Under ideal conditions with perfectly stable lamps and instruments, the 2 formulae lead to the same result. The choice of formula's is left to the user's scientific judgement. Using Formula 9 may offer a more direct insight of the homogeneity of the irradiance.

6.4.4 Calibration conditions and optional correction of reference operating conditions

For a calibration laboratory performing indoor calibration there are several commonly used ways to report calibration results, (sensitivity and its uncertainty), and the conditions in which the reported sensitivity is valid; this can be either the calibration conditions or:

Option 1 a:

— the reported sensitivity is valid under conditions similar to the outdoor calibration conditions under which the reference pyranometer was calibrated.

— if the relevant instrument properties (most importantly temperature response, directional response, spectral response, tilt response) are included in the calibration uncertainty of the reference instrument, no additions to the total calibration uncertainty need to be introduced. Of course the uncertainty of the indoor transfer procedure shall be added to the total calibration uncertainty.

Option 1 b:

— the reported sensitivity is valid under conditions similar to the outdoor calibration conditions under which the reference pyranometer was calibrated,

  similar to option 1 a, however, when the uncertainty of the reference instrument does not include all uncertainties associated with the instrument specs (or individual systematic errors) these may be added or accounted for. This may lead to additional contributions to the calibration uncertainty.

  For example, if the reference pyranometer has been calibrated at 10 °C, and the indoor calibration temperature is 25 °C, the calibration reference temperature (conditions specified in the certificate) for the test pyranometer is 10 °C. As the pyranometers will not have exactly the same temperature dependence, an uncertainty may be added to take this into account. This uncertainty may for example be calculated using the specification of the class in ISO 9060, or from experimentally determined instrument properties.

Option 2:

— the reported sensitivity is valid for standardised reference-operating conditions chosen by the calibration laboratory (for example horizontal installation, 20 °C instrument temperature, normal incidence radiation), or valid for specific measurement conditions.

— possibly including corrections for systematic errors such as the change of sensitivity of the reference pyranometer to the specific reference-operating conditions,

— while adding an uncertainty accounting for the differences in conditions (both for the reference pyranometer and the newly calibrated test pyranometer),

This last contribution to the uncertainty of option 2 takes into account that properties may significantly differ between instruments of the same model. This approach may have the benefit for the user of simplifying the measurement uncertainty evaluation when instruments are used in the field.

6.4.5 Uncertainty evaluation

The uncertainty evaluation of indoor calibration shall at least show

— uncertainty of the sensitivity of the reference pyranometer,

— uncertainty related to transfer of the reference to the indoor conditions, and

— the uncertainty of the method.

In case of re-calibration it is recommended to compare the previous calibration result to the new calibration result. See Annex F for an example of uncertainty evaluation for indoor calibration.

7 Outdoor calibration (Type B)

7.1 Introductory remarks on outdoor calibration

Outdoor calibrations may be carried out under different atmospheric conditions and mounting conditions of the instrument.

The outdoor calibration uncertainty depends on environmental factors and site-specific conditions. For a the most accurate result it is essential that the measurement is done over a sufficiently long period of time, and with sufficient clear sky exposure at low angles of incidence. In outdoor calibration, the ambient temperature, angle of incidence and stability of the source are not under control (except angle of incidence when using method B3). Users of outdoor calibration methods will typically have to perform an individual uncertainty evaluation of each calibration, taking environmental conditions into account.

Class B and C pyranometers may have significant tilt and directional errors, so that for these pyranometers the tilt angle and angle of incidence of direct radiation are relevant. If the pyranometer is used in a particular, for example tilted, condition an outdoor calibration against a higher accuracy reference pyranometer under the same condition may compensate for directional- and tilt errors. Even Class A sensors may have significant zero offset A. This offset may be reduced by ventilation, and instruments employed with a ventilator may therefore best be calibrated in a ventilated condition. Outdoor calibration at a fixed tilt angle or at normal incidence may be useful to attain higher irradiance levels.

The reported sensitivity is valid for conditions during this calibration. These may also be corrected to other reference-operating conditions. In that case this change shall be accounted for in the calibration uncertainty.

ISO 9846[4] describes several outdoor calibration methods of pyranometers against pyrheliometers. If performed using pyrheliometers with a low calibration uncertainty, this method potentially leads to the lowest calibration uncertainties, typically of around 1 %.

7.2 Reference pyranometers for outdoor calibration

Preferably, the reference pyranometer for outdoor calibration should be of a higher accuracy class (according to ISO 9060) than the test pyranometer, and calibrated according to ISO 9846. It is recommended that the dependence of its sensitivity on temperature, irradiance, tilt, spectrum and angles of incidence are documented. Spectrally non-flat pyranometers should preferably be calibrated against spectrally flat pyranometers.

In outdoor calibration, there are no special requirements for the reference pyranometer. The measurement uncertainty of the reference pyranometer under the specific outdoor conditions during calibration is the relevant factor.

If the calibration of the reference pyranometer refers to conditions different from those present during the calibration of the test pyranometer, this should be taken into account in the uncertainty evaluation of the calibration.

7.3 Outdoor calibration systems

7.3.1 Site selection for outdoor calibration

Preferably, the site should have a horizon free from obstructions at the relevant solar azimuth and zenith angles[3]. As the calibration method of this document is by comparison to a similar instrument, a pyranometer, the requirements for the site are not strict. There should be no nearby objects reflecting radiation to the pyranometers.

7.3.2 Tracking for normal incidence calibration (type B3)

A solar tracker shall keep the reference pyranometer and test pyranometer normal to the sun. The tracking accuracy shall be such that deviations from the solar centre do not exceed ±2°.

7.4 Outdoor calibration procedures

7.4.1 Calibration procedure requirements (B1, B2, B3)

Ensure that the azimuth references (e.g. connectors) of the pyranometers are aligned according to the instrument specific recommendations.

Check alignment in the horizontal position. If the instrument body is not used for alignment, use the instrument bubble level.

It is recommended to measure the temperature of the pyranometer bodies and of the environment.

NOTE In outdoor calibration, a common convention is to use the electrical connector as the azimuth reference and to point it towards the nearest pole when calibration is done in the horizontal position or downwards when the pyranometer is tilted[3].

Reference and test pyranometers are not necessarily of the same model.

Corrections might be used to reduce systematic errors such as temperature, incidence angle and spectral errors. If such corrections are applied to the test pyranometer, the same corrections shall be used during the calibration and the later applications of the pyranometer. Corrections might be able to noticeably reduce the calibration uncertainty and later the measurement uncertainty if the test instrument has systematic errors, as e.g. in the case of photodiode pyranometers.

Laboratories may calibrate under the calibration conditions, environmental, angle of incidence etc, of their choice. The accuracy of the test pyranometer for conditions different from these calibration conditions might be significantly reduced depending on the instrument and the optionally applied corrections, as mentioned above.

For non-spectrally flat pyranometers the importance of the calibration conditions is even higher than for spectrally flat pyranometers. It is therefore common to calibrate non-spectrally flat pyranometers around air mass 1,5. (e.g. air mass range of 1,8 to 1,3, or 1 h before or after air mass 1,5) and for high irradiances. In particular if corrections for temperature, spectrum and incidence angle are applied, long calibration data sets covering the conditions expected in the later application can also be of advantage.

Mount the reference pyranometer and the test pyranometer outdoors in the same plane.

The calibration platforms may remain horizontal for calibration type B1, be changed to a certain (even varying) tilt for calibration type B2, or be attached to a solar tracker for normal-incidence calibration type B3.

The readings of test and reference pyranometer shall be measured nearly simultaneously. If the same data logger is used for both instruments sampling both signals within the same second is sufficient. If different data loggers are used for both devices their clocks shall be synchronized with an error of less than 1 s and the same sampling interval should be used. For simplicity such measurements are called simultaneous in the text below.

7.4.2 Outdoor horizontal calibration procedure (type B1)

7.4.2.1 Under stable cloudless sky conditions

Under stable nearly cloudless sky conditions, simultaneously collect a minimum of 15 data series each 10 min to 20 min long, with 20 or more records in each series. At least 240 records shall pass the filters defined below for the data rejection (see 7.4.5.4). At least 30 % of the records shall be recorded within ±2 h around solar noon, 40 % to 60 % before the solar noon and 40 % to 60 % after the solar noon.

Take these measurement series over a minimum of a 2-day period, limited to solar zenith angles smaller than 70° (see also Annex B). If the test pyranometer will be used mostly for high solar zenith angles higher solar zenith angles are also allowed.

In case there is a requirement to cover a large range of environmental conditions the measurement may be extended over a longer period. This might be of interest for example for spectrally non-flat instruments.

7.4.2.2 Under unstable sky conditions with some clouds

Under unstable sky conditions with clouds, simultaneously sample both instruments and integrate over a time interval between 1 min to 5 min to obtain the records. To ensure that clouds are not affecting the calibration, data may only be taken if there are no clouds close to the Sun. This can be checked by observing the sky with the bare eye or with a camera ensuring that there are no clouds within 30° from the sun. Alternatively, the calibration data can be filtered using co-located global horizontal solar irradiance, G, direct normal irradiance, G_b, and/or diffuse horizontal irradiance, G_d, measurements. Records shall be used for the calibration that fulfil all of the following conditions:

— $G_d/G < 0,4$;

— $G_b > 500$ W/m²;

— maximum variation of G_b in a series <200 W/m²;

The set of records used for calibration consists of a minimum of 15 series of 20 or more records that represent steady radiation over the calibration period. At least 240 records shall pass the filters given above and those defined below for the data rejection (see 7.4.5.4). At least 30 % of the records shall be recorded within ±2 h around solar noon, 40 % to 60 % before the solar noon and 40 % to 60 % after the solar noon.

Take these data series over a minimum of 2-day period, limited to solar zenith angles smaller than 70°. If the test pyranometer will be used for measurements at high solar zenith angles, calibration at higher solar zenith angles is also allowed.

In case there is a requirement to cover a large range of environmental conditions the measurement may be extended over a longer period. This might be of interest for example for spectrally non-flat instruments.

7.4.2.3 Cloudy sky conditions

For cloudy sky conditions take simultaneous samples on both instruments and integrate over a time interval between 10 min to 1 h to obtain the records. The set of records used for calibration consists of a minimum of 10 series of one day with 10 or more records, over the calibration period with different solar elevation angles, and different types of cloudiness while the hourly mean of global irradiance is greater than 100 W/m². At least 100 records shall pass the filters given above and those defined below for the data rejection (see 7.4.5.4).

NOTE Calibrations under cloudy sky conditions typically result in a higher calibration uncertainty than calibrations under mostly cloud free conditions and are not recommended unless the test pyranometer will be used mainly for cloudy conditions.

7.4.3 Outdoor tilted calibration procedure (type B2)

Before the calibration, check that the radiation reflected by the ground surface at the locations of both instruments are the same e.g. by changing their positions.

Take records of hemispherical solar radiation in accordance with 7.4.2.1 or 7.4.2.2 depending on the sky conditions.

7.4.4 Outdoor normal incidence calibration procedure (type B3)

Ensure that all data are taken while instrument output exceeds 600 W/m^2 and centre the data set around solar noon.

Before the calibration, check that the radiation reflected by the ground surface at the locations of both instruments are the same by changing their positions.

Otherwise take records of hemispherical solar radiation in accordance with 7.4.2.1 or 7.4.2.2 depending on the sky conditions.

7.4.5 Calculation of the sensitivity

7.4.5.1 General

If a single sensitivity is calculated over a range of solar angles of incidence, for example, when using daily sums, the daily average solar zenith angle shall be reported. A way to calculate the daily average solar zenith angle is given in Annex B. Annex D shows examples of data with outliers and large standard deviation.

The following calculations are required.

7.4.5.2 Calculating output ratio's

A first step applies to every pair of records of test and reference pyranometer.

From each record, *i*, calculate the ratios given by Formula (12):

$$S_{\mathrm{t},i} = \frac{V_{\mathrm{t},i}}{V_{\mathrm{r},i}} S_{\mathrm{r}} \tag{12}$$

where

V_i is the record of the output of the pyranometer output in arbitrary units;

r is the reference pyranometer;

t is the test pyranometer;

S_{r} is the sensitivity of the reference pyranometer, possibly with a correction factor for the conditions during calibration e.g. for temperature dependence.

As described in 4.2, Formula (2), offsets may act on *V*. These are then included in the above formula V_i.

7.4.5.3 Data rejection

First, reject all records which have been subject to operational problems for both pyranometers, and which do not comply with the specifications from 7.4.2 to 7.4.4. As a second step, determine the average sensitivity of the test pyranometer within measurement series number j consisting of the remaining N_j records using the Formula (13):

$$S_{avg,j} = S_r \sum_{i=1}^{i=N_j} \frac{V_{t,i}}{V_{r,i}} \tag{13}$$

The purpose of these $S_{avg,j}$ calculation is the outlier rejection only. For the sensitivity calculation $S_{t,i}$ valid records shall be used with the same statistical weight.

7.4.5.4 Outlier rejection

Reject those data for which $S_{t,i}$ of Formula (12), deviates by more than ±2 % from $S_{avg,j}$ of Formula (13). The series, j, includes the record, i.

7.4.5.5 Statistical analysis

Determine the stability of the calibration conditions by calculating the standard deviation of $S_{t,i}$ over all records used for calculation of the sensitivity (all data used in Formula (3), not only the ones from the clean data after outlier rejection). The statistical distribution (standard deviation) of S_t around its mean value represents the stability of the conditions during the calibration, and also includes contributions of the measurement capabilities of the test pyranometer. This statistical distribution (standard deviation) shall be input to the uncertainty evaluation.

7.4.5.6 Calculation of the sensitivity

Derive the final sensitivity of the test pyranometer from the total number, m, of retained records retained after applying the outlier rejection (see 7.4.5.4) from Formula (14):

$$S_{t,final} = \frac{1}{m} \sum_{i=1}^{i=m} S_{t,i} \tag{14}$$

7.4.6 Calibration conditions and optional correction of reference operating conditions

7.4.6.1 Choice and optional correction of reference conditions: temperature

The reported sensitivity may refer to reference conditions other than the actual instrument temperature during calibration. If during a calibration the test pyranometer's temperature, T, significantly deviates from the desired and reported reference value, T_N, and if the temperature response or its limits of the test pyranometer is known, then a correction factor for this temperature dependence may be used. In such case, additional uncertainties of the correction shall be taken into account in the uncertainty evaluation.

7.4.6.2 Choice and optional correction of reference conditions: angle of incidence

In the outdoor measurement methods of this document, the relative contributions of direct and diffuse radiation to the sensitivity are not known without further additional measurements. Without such additional measurements it is therefore not possible to accurately correct for incidence angle effects.

7.4.7 Uncertainty evaluation

The uncertainty evaluation of outdoor calibration shall at least show

— uncertainty of the sensitivity of the reference pyranometer,

— uncertainty related to use of the reference pyranometer under the outdoor conditions during calibrations,

— the uncertainty of the method, and

— the uncertainty related to the records used to determine the sensitivity (statistical distribution of the measurement results as mentioned in 7.4.5.5).

For outdoor calibration the uncertainty evaluation for one instrument may not be used for other instruments; data rejection and statistical analysis and the relating uncertainty evaluations shall be performed for every calibration individually. Annex E contains more detailed comments.

8 Calibration certificate

The certificate of calibration shall as a minimum state the following information on

a) the test pyranometer:

   — model and serial number;

b) the reference pyranometer:

   — model and serial number;

   — calibration hierarchy and traceability;

   — corrections applied (if any) for example from calibration conditions of the reference pyranometer to the calibration conditions of the present calibration;

c) the procedure:

   — identification of the calibration procedure (i.e. reference to this document, calibration type: indoor A1-A2, outdoor B1-B2-B3, or an internal documented procedure);

   — location;

   — date of calibration;

   — calibration conditions (i.e. -averages of – and minimum and maximum of tilt angle, angle of incidence, temperature, irradiance);

   — only for non-spectrally flat instruments in outdoor calibrations: the spectrum or the conditions affecting the spectrum (e.g. aerosol optical depth, precipitable water vapor, Linke turbidity, cloud conditions);

   — identification of the person authorising the report;

d) the result of the calibration:

   — sensitivity;

   — uncertainty evaluation of sensitivity;

   — reference-operating conditions (if different from the calibration conditions);

   — for outdoor calibration only: the standard deviation.

Annex A
(informative)

Examples of calibration systems using artificial sources

A.1 General

Suitable systems that have been used in different laboratories to calibrate pyranometers indoors are described in A.2 and A.3.

A.2 Systems using a direct beam source (type A1)

A.2.1 System and procedure example 1

A calibration system and calibration procedure are described in Reference [8]. The vertical beam is produced by a 150 W metal-halide lamp fed by an AC voltage stabilizer with reflector (concave mirror) above the lamp.

The reference and test pyranometers are mounted horizontally on a table which can rotate to exchange the position of both instruments. The distance between the reflector and pyranometers is 1,2 m, and the irradiance at the pyranometers is approximately 500 W/m^2.

The procedure is based on a sequence of records as shown in Table A.1.

Table A.1 — Measurement procedure

Sampling time after start s	Reference pyranometer		Test pyranometer		Remarks
	unshaded	shaded	unshaded	shaded	
90	$V_{r,u}$	–	$V_{t,u}$	–	Pyranometers in initial position
180	-	$V_{r,s}$	-	$V_{t,s}$	
270	$V'_{r,u}$	–	$V'_{t,u}$	–	Pyranometers transposed
360	-	$V'_{r,s}$	-	$V'_{t,s}$	

The calibration is considered stable if the ratio given by Expression (A.1):

$$\frac{(V_{r,u} - V_{r,s})(V_{t,u} - V_{t,s})}{\left(V'_{r,u} - V'_{r,s}\right)\left(V'_{t,u} - V'_{t,s}\right)} \qquad \text{(A.1)}$$

deviates no more than ±*k* % from unity, where *k* is at most 0,5. Lower values represent a higher stability.

A calibration and measurement capability of 1 % can be obtained, see NOTE.

In case photodiode pyranometers are calibrated, thermal stabilization in not required, so time of sampling after start is shortened, unshaded measurements are not performed, since zero offsets are do not appear, and only one position is used at which reference and test instruments are measured sequentially.

NOTE Calibration and measurement capability (CMC): demonstrated measurement uncertainty, with coverage probability of 95 %, in a given measurement point or measurement range, calculated according to EA-4/02 “Evaluation of the Uncertainty of Measurement in Calibration”[9].

A.2.2 System and procedure example 2

A vertical light beam is produced by a 600 W Halogen lamp, located in a ventilated lamp compartment. The lamp is stabilized using a high-stability power supply[10].

Reference and test pyranometers are located in the sensor compartment, which is then closed so that no externally generated light enters this compartment. Sensors are placed on spacers so that their position is known and sensor height relative to the lamp remains the same.

Between the lamp compartment and the sensor compartment there is an automated shutter. A measurement and control unit takes care of process control and data acquisition as well as data quality assurance. Further process control and entry of data by the operator is via a user interface on the operator's PC screen. Instrument positions are manually exchanged.

The measurement procedure follows 6.4.1 and 6.4.2, and calculation of the sensitivity is according to 6.4.3 with k = 0,01. A CMC (see note in A.2.1) of less than 1 % can be attained.

A.2.3 System and procedure example 3

Meteorological Observatory Lindenberg, part of the Deutscher Wetterdienst operates the following facility[11].

The directed vertical beam (divergence, ±1,5°) is produced by a combination of

a) a 450 W xenon lamp (Osram type X BO) with condenser optics and air cooling, stabilized by feedback of the lamp output (monitoring of a split beam by a silicon photodiode),

b) an optical integrating device (to homogenize the radiant flux density of the beam), and

c) a flat mirror tilted to 45° (to turn the beam from horizontal to vertical).

The reference and test pyranometers are mounted horizontally side by side on a platform which can be translated so that the pyranometers are alternately exposed to the beam. The centres of the receivers of both pyranometers shall have the same coordinates when they are exposed to the beam (diameter, approximately 10 cm; irradiance, 700 W/m^2; homogeneity of irradiance, ±2 % within a circle of 24 mm). The pyranometer platform and the mirror are installed in a climatized room which ensures constant environmental conditions, and a wall painted black which reduces stray light.

The procedure for taking records is shown in Table A.2; an alternative procedure is shown in Table A.3. The tables are examples.

Table A.2 — Measurement procedure

Sampling time after start min	Reference pyranometer		Test pyranometer		Remarks
	unshaded	shaded	unshaded	shaded	
2		$V_{r,s}$			
4	$V_{r,u}$				
6		$V_{r,s}$			
8	$V_{r,u}$				
10		$V_{r,s}$			
					Exchange of position
12				$V_{t,s}$	
14			$V_{t,u}$		
16				$V_{t,s}$	
18			$V_{t,u}$		
20				$V_{t,s}$	
22			$V_{t,u}$		
24				$V_{t,s}$	
					Exchange of position
26		$V_{r,s}$			
28	$V_{r,u}$				
30		$V_{r,s}$			
32	$V_{r,u}$				
34		$V_{r,s}$			

Table A.3 — Alternative procedure

Sampling time after start min	Reference pyranometer		Test pyranometer		Remarks
	unshaded	shaded	unshaded	shaded	
2		$V_{r,s}1$	$V_{t,u}1$		Calculate
4	$V_{r,u}2$			$V_{t,s}2$	*k*2
6		$V_{r,s}3$	$V_{t,u}3$		
8	$V_{r,u}4$			$V_{t,s}4$	*k*4
10		$V_{r,s}5$	$V_{t,u}5$		
12	$V_{r,u}6$			$V_{r,s}6$	*k*6
14		$V_{r,s}7$	$V_{t,u}7$		
16	$V_{r,u}8$			$V_{t,s}8$	*k*8
18		$V_{r,s}9$	$V_{t,u}9$		
20	$V_{r,u}10$			$V_{t,s}10$	*k*10
22		$V_{r,s}11$	$V_{t,u}11$		-------------
					mean

A.2.4 System and procedure example 4

A reference pyranometer is calibrated against the primary reference sensor, according to the sun-and-shade method under ISO 9846.

The test pyranometer is calibrated against a calibrated reference pyranometer of the same model using a 1 000 W/m^2 AAA solar simulator (AM1,5 G ± 0,0075 G temporal stability) with automatic shutter. The reference and test pyranometers are installed in horizontal position on an automatic 2-dimensional optical stage with high positioning precision. By alternating the position of the reference pyranometer with the test pyranometer multiple times, the output signal of both pyranometers are recorded and used to calculate the sensitivity. The calibration conditions are maintained constant (e.g. ambient temperature is controlled within 25 °C ± 3 °C and normal incidence irradiance 1 000 W/m^2)[12].

With this system and procedure, a CMC (see note in A.2.1) of 0,59 % can be attained.

A.3 Systems using an integrating sphere source (type A2)

A.3.1 system and procedure example 1

Reference [13] describes an integrating sphere source and measurement procedure:

The source is 2,4 m diameter integrating hemisphere. It comprises 12 200 W and 12 300 W tungsten lamps positioned near the rim of the hemisphere. Up to four pyranometers can be mounted on the instrument pedestal stand in the centre of the sphere such that each instrument is at the same height, above the direct lamp exposure and subject only to the diffuse irradiance reflected symmetrically off the interior of the upper part of the sphere. Water circulators are used to control the instrument temperatures and the sphere walls. Annual testing ensures that the irradiance in the dome interior is homogeneous. Instrument positions therefore do not need to be exchanged.

The transfer standard reference pyranometer and up to three test pyranometers (all of the same model type) are positioned on a temperature-controlled pedestal symmetrically located in the centre of the integrating sphere. Be sure the instrument domes are cleaned. Connect the instruments to the data acquisition system. Turn on the water circulators to the instrument stand and the sidewalls of the integrating hemisphere. Power on the lamps and set the voltage controller to 110 VAC creating a diffuse irradiance of approximately 600 W/m^2 to 700 W/m^2. Prior to the data run, cap the instruments and measure the initial zero readings. Run the data run and record the voltages of the reference and test pyranometers. After the run, cap the instruments and measure the final zero readings. Average the initial and final zeros and subtract from the instrument voltages in the data run.

Annex B
(informative)

Calculation of daily average zenith angle

A representative angle for any given calibration site may be determined by calculating the mean of the cosine of the zenith angle weighted with the cosine of the same angle to give a weight in approximate proportion to the global irradiance. This condition is expressed mathematically by Formula B.1) as follows:

$$\left(\overline{\cos\theta}\right)=\frac{\int_{\omega_1}^{\omega_2}\cos^2\theta\, d\omega}{\int_{\omega_1}^{\omega_2}\cos\theta\, d\omega} \quad \text{(B.1)}$$

where ω_1 and ω_2 are the integration limits (in radians) defining the time period over which the average is calculated and θ is the solar zenith angle[1)] given by:

$$\cos\theta = a + b\cos\omega$$

where

a $=\sin\phi\sin\delta$;

b $=\cos\phi\cos\delta$;

ω is the solar hour angle in radians;

ϕ is the latitude (north positive, south negative);

δ is the solar declination.

It is readily shown that for the case that $\omega_1 = 0$ (solar noon) Formula (B.1) reduces to:

$$\left(\overline{\cos\theta}\right)=\frac{\left(a^2+b^2/2\right)\omega_2+\sin\omega_2\left[\left(b^2/2\right)\cos\omega_2+2\,a\,b\right]}{a\,\omega_2+b\,sin\,\omega_2} \quad \text{(B.2)}$$

The above expression for $\omega_1 = 0$ was evaluated with $\omega_2=\cos^{-1}\{[\cos(\theta_2)-a]/b\}$, where is the hour angle ω_2 in radian and θ_2 the zenith angle corresponding to 70°. Using solar declination values δ given by Duffie and Beckman[6] as representative of each month; the results (rounded to 5°) are shown in Table B.1.

The results confirm that the method of selecting the *S(i)* values at a solar zenith angles of 40° to 45°, as used in practice, is appropriate for mid-northern/southern latitudes throughout the world. They also highlight the importance of the directional response specification of pyranometers to be used poleward of latitude 30°, particularly during the winter months. These results lend support to Zerlaut[14].

1) Formula (B.1) represents a weighted average of the form $\sum(w\,x)/\sum w$, where the weight $w = 1\times\cos\theta$ can be thought of as clear sky solar radiation with noon value 1 kW/m^2 and cos as the quantity whose weighted average value is being evaluated.

Table B.1 — Weighted daily average solar zenith angle for different latitudes and months

Month in the northern hemisphere	Weighted daily average solar zenith angle (degrees) for $\acute{E}_1 = 0$ and $\omega_2 = \cos^{-1}\{[\cos(\theta_2) - a]/b\}$ the hour angle corresponding to $\theta_2 = 70°$ at a latitude of:						Month in the southern hemisphere
	0°	**15°**	**30°**	**45°**	**60°**	**75°**	
January	40	45	55	65	—	—	July
February	35	45	50	60	—	—	August
March	35	40	45	55	65	—	September
April	35	35	40	45	55	65	October
May	40	35	35	40	50	60	November
June	40	35	35	40	50	60	December
July	40	35	35	40	50	60	January
August	35	35	40	45	55	65	February
September	35	35	45	50	60	—	March
October	35	40	50	60	—	—	April
November	40	45	55	65	—	—	May
December	40	50	60	—	—	—	June

Annex C
(informative)

Introduction of a new pyranometer sensitivity

Users should know that well-maintained thermal pyranometers are stable instruments with very limited drift of sensitivity over time.

When a pyranometer is recalibrated, it is recommended to compare the new sensitivity to its previous sensitivity. Before changing the sensitivity applied to generate data, the proposed change should be compared to the calibration uncertainty. If the proposed change in sensitivity is small compared to the calibration uncertainties, the change may be rated "not significant". If a change is introduced this could lead to an unnecessary discontinuity in the measured data. Making such comparison only the uncertainty related to the calibration methods of the calibrated instrument and the calibration reference should be considered. Systematic errors (such as the WRR uncertainty relative to SI) should be excluded from the analysis.

Changing the instrument sensitivity may lead to discontinuities in data series and as a consequence to discontinuities of derived quantities such as the Performance Ratio measurements for PV systems.

If a new calibration result, a sensitivity, is different from the previous result there are several options open to the user:

Option 1: the new sensitivity and its uncertainty are introduced without any further consideration. This is common practice in metrology. A scale change and discontinuity in data series may then occur, but is accepted (see note 1).

Option 2: the recalibration is considered as a verification of the sensitivity used at that moment (a "conformity test"). If the new sensitivity passes the decision rule of the conformity test, (see note 1), the two results are metrologically compatible and original pyranometer sensitivity may be retained. Possibly this results in a more consistent data series than when working according option 1. However, when working according to this option the calibration uncertainty of the instrument shall be carefully reviewed. This uncertainty cannot be lower than that of the recalibration.

If several independent recalibrations consistently differ from the original, a new sensitivity may be introduced as per option 1.

Option 3: the user makes an elaborate evaluation and decides when to apply the new sensitivity e.g. after a certain event.

If a significant change in sensitivity is found (see the decision rule of note 1) it is recommended to investigate how and when this change has occurred. The data may be treated accordingly. If an event can be pinpointed that triggered the change, any data collected after that event can be reprocessed using the new sensitivity. If no specific cause of the change can be found, the user can either introduce the new sensitivity from the date of the recalibration and have a step-change in the data series, or if a gradual drift in sensitivity is more likely or evident from successive calibrations, the user can re-process the data, interpolating the sensitivity over the time between original and new calibration and applying a sensitivity that gradually changes over time to obtain an as-realistic-as-possible data series.

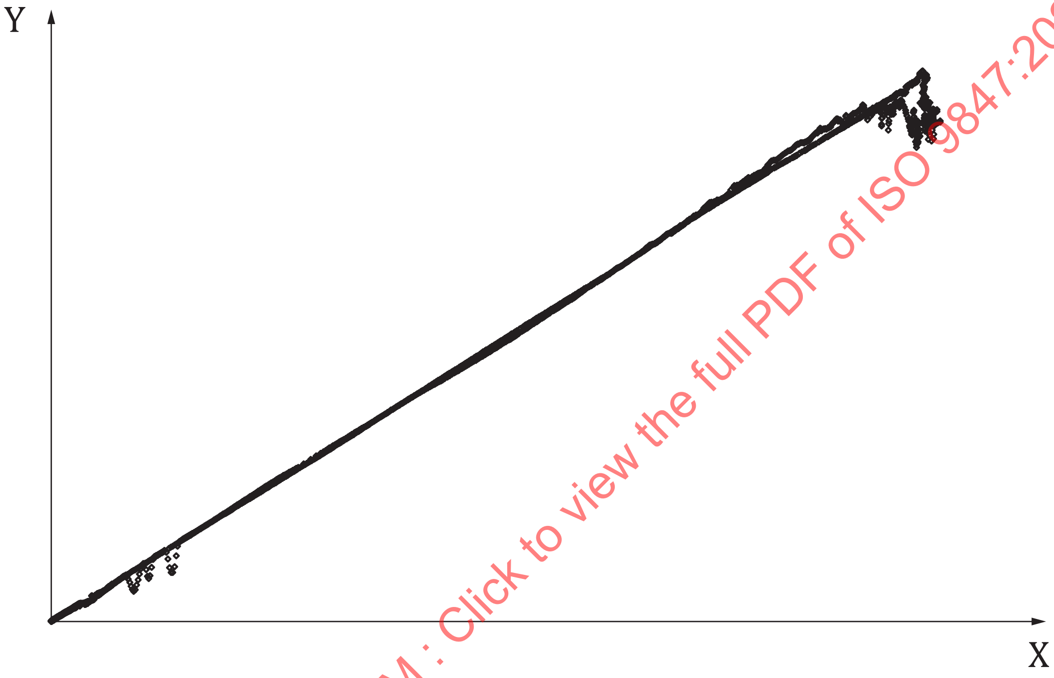
NOTE To decide if the new and old sensitivities S(new) and S(old), significantly differ, or are metrologically compatible[1], the E_n decision rule can be used[9][15]. The uncertainty, U, only includes the uncertainty of the methods, not of the scale. In solar energy it is customary to use the expanded measurement uncertainty, U, with a coverage factor $k = 2$.

$$E_n = \frac{\left| S(\text{new}) - S(\text{old}) \right|}{\sqrt{U(\text{new})^2 + U(\text{old})^2}} < 1$$

Annex D
(informative)

Data quality review for outdoor calibration

During outdoor calibrations of pyranometers (and other solar irradiance sensors) some situations may lead to results having a large uncertainty budget. These may be treated as statistical uncertainty type A, but are better avoided. Some examples are illustrated in the following Figures D.1, D.2 and D.3:



Key

X solar irradiance as measured by calibration reference pyranometer

Y solar irradiance as measured by the test pyranometer

Figure D.1 — Effect of moisture condensation in the internal face of the dome of a thermoelectric pyranometer (unexpected result)