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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

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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):

$$S = (V - V_0)/G \quad (2)$$

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 %.