INTERNATIONAL STANDARD

**ISO
9846**

Solar energy — Calibration of a pyranometer using a pyrheliometer

Énergie solaire — Étalonnage d'un pyranomètre utilisant un pyrhéliomètre

Contents

Foreword

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

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

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

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

Introduction

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

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

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

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

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

Solar energy — Calibration of a pyranometer using a pyrheliometer

1 Scope

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

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

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

2 Normative references

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

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

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

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

3 Definitions

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

3.1 calibration of a radiometer: Determination of the responsivity (or the calibration factor, as its reciprocal) of a radiometer under well-defined measurement conditions.

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

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

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

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

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

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

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

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

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

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

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

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

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

4   Selection of methods

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

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

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

5   Alternating sun-and-shade method

5.1   Principle

The pyranometer under test is compared with a pyrheliometer measuring direct solar irradiance. The voltage values from the pyranometer that correspond to direct solar irradiance are derived from the difference between the measured values of hemispherical solar irradiance and the diffuse solar irradiance (see note 1, 3.8). These values are measured periodically by means of a movable sun shade disc. For the calculation of the responsivity, the difference in irradiance components is divided by the measured direct solar irradiance normal to the receiver plane of the pyranometer.

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

5.2   Apparatus

5.2.1   Pyranometer.

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

5.2.2   Pyrheliometer.

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

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

5.2.4   Shade disc device, meeting the following requirements:

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

b) The radius r of the shade disc should be larger than the radius of the outer glass dome of the pyranometer by a minimum of $d \tan(0,5°)$ to allow for the divergence of the sun beam and small tracking errors.

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

NOTE 2   A fixed "shade slope angle", corresponding to the slope angle of the pyrheliometer, can only be

stated for pyranometers which are operated in a position normal to the sun's ray. For other pyranometers, the shade slope angle varies according to the angle of incidence of the ray on the receiver plane.

d) Those parts of the disc holder which obscure the field-of-view angle of the pyranometer should be as small as possible in order to restrict the disturbance of the signal to less than 0,5 %. Similar regard to interference with other neighbouring instruments should be considered.

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

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

5.2.5 Data acquisition system.

To acquire the values, in millivolts, of the radiometer readings, the system should be equipped with a precise digital voltmeter with a resolution of 1 µV and an uncertainty of 0,1 % of the pyranometer's calculated output at 1 100 W m^{-2}. High temperature stability is required for outdoor operation. The data sampled from all radiometers should be recorded within about 1 s. A time resolution for calculating the corresponding solar elevation angle with an uncertainty of less than 0,1° is required. For documenting the variation of the measured values during the calibration period, the data should be appropriately recorded.

5.3 Measurement conditions

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

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

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

5.4 Measurement site

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

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

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

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

5.5 Installation

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

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

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

5.6 Calibration procedure

5.6.1 Preparatory phase

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

— acclimatization of the radiometers, electronics and data acquisition system;

— adjustment of radiometers, solar tracker and shade disc device;

— checking of the electrical connections, test voltages and zeroing tests;

— final cleaning of the optical windows.

5.6.2 Measurement phase (single series)

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

During the measurement phase

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

— if shaded, the signal for diffuse solar irradiance $E_{D, \beta}$ (including reflected solar irradiance if $\beta \neq 0$), $(n + 1)$ values. Read at the end of each shading interval t_0 (see graph below)

— if exposed to hemispheric solar radiation, the signal for hemispherical solar irradiance $E_{G, \beta}$, n values. Read at the end of each exposure to hemispherical solar radiation interval t_0 (see graph below);

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

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

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

The measurement sequence is illustrated in the following scheme:

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

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

The choice of t_0 should consider the setting conditions during fine weather and cloudless conditions.
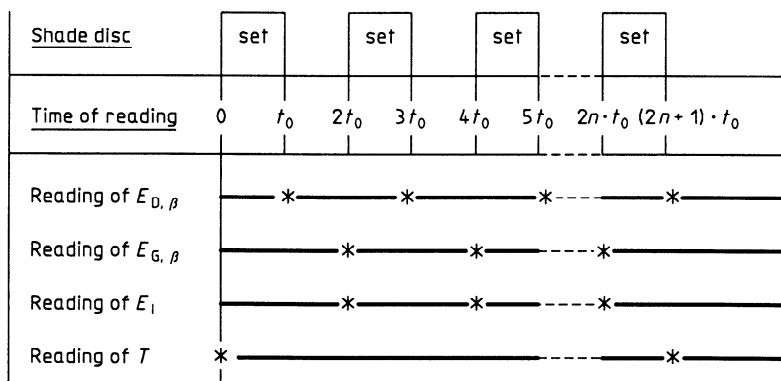
Generally, for commercially available pyranometers t_0 lies between 1 and 4 min; t_0 may be reduced by wind or the artificial ventilation of the instrument.

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

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

5.6.3 Number of series

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

5.7 Determination of the calibration factor

5.7.1 Evaluation of a single series

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

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

$$\overline{R}_S = \frac{\sum\limits_{i=1}^{n} \{V_{G,\beta}(2i) - 0.5[V_{D,\beta}(2i-1) + V_{D,\beta}(2i+1)]\}}{\sum\limits_{i=1}^{n} V_I(2i) \cdot F_p \cdot \cos[\eta(2i)]} \quad \ldots (2)$$

where

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

total number of reading intervals $(2n + 1)$.

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

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

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

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

5.7.2 Evaluation of the final results

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

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

If a reduction formula $f(T,T_n)$ is available, and there are some series in which the temperature deviates significantly from the desired value T_n, then apply $f(T,T_n)$ to each R_S according to:

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

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

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

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

and the responsivity R.

6 Continuous sun-and-shade method

6.1 Principle

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

6.2 Apparatus

6.2.1 Pyranometer.

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

6.2.2 Pyrheliometer.

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

6.2.3 Solar tracker.

See 5.2.3.

6.2.4 Shade disc device.

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

6.2.5 Data acquisition system.

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

6.3 Measurement conditions

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

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

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

6.4 Measurement site

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

6.5 Installation

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

6.6 Calibration procedure

6.6.1 Preparatory phase

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

6.6.2 Measurement phase (single series)

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

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

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

— direct solar irradiance signal V_I from the reference pyrheliometer.

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

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

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

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

6.6.3 Number of series

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

6.7 Determination of the calibration factor

6.7.1 Evaluation of a single series

a) Eliminate from the calculation all sets which deviate from the corresponding series mean by more than 5 %. Discard any series if more than 50 % of the sets have been eliminated.

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

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

where

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

ceiver plane of the test pyranometer at the time of the reading of set i (see annex B);

F_p	is the calibration factor of the reference pyrheliometer;
$V_I(i) \cdot F_p \cdot \cos \eta(i)$	is the direct solar irradiance projected on the receiver plane of the pyranometer.

6.7.2 Evaluation of the final results

Evaluation is carried out as specified in 5.7.2.

7 Certificate of calibration

The certificate shall state as a minimum the following information on

a) the test pyranometer:

— manufacturer, type and serial number;

— position (inclination angles, azimuthal orientation and tracking);

— special remarks on the state of the instrument;

b) the reference instruments:

— manufacturer, type and serial number;

— hierarchy of traceability;

— shade disc geometry;

— corrections applied;

c) the procedure:

— type of procedure (i.e. reference to this International Standard);

— site (latitude, longitude and altitude);

— date and time of calibration;

— number of series;

— ranges of measurement parameters (solar elevation angle, hemispherical solar irradiance, turbidity and temperature);

— application of reduction formulae;

d) the result of the calibration:

— responsivity, expressed in microvolts per watt per square metre, and calibration factor, ex-