IEC 60904-4

Edition 2.0 2019-11
REDLINE VERSION

INTERNATIONAL STANDARD

Photovoltaic devices –
Part 4: ~~Reference solar~~ Photovoltaic reference devices – Procedures for establishing calibration traceability

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colour inside

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Part 4: ~~Reference solar~~ Photovoltaic reference devices – Procedures for establishing calibration traceability

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.160 ISBN 978-2-8322-7608-2

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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PHOTOVOLTAIC DEVICES –

Part 4: ~~Reference solar~~ Photovoltaic reference devices – Procedures for establishing calibration traceability

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

International Standard IEC 60904-4 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This second edition cancels and replaces the first edition published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) modification of standard title;
b) inclusion of working reference in traceability chain;
c) update of WRR with respect to SI;
d) revision of all methods and their uncertainties in Annex A;
e) harmonization of symbols and formulae with other IEC standards.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
82/1618/FDIS	82/1638/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60904 series, published under the general title *Photovoltaic devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigendum of September 2020 have been included in this copy.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

PHOTOVOLTAIC DEVICES –

Part 4: ~~Reference solar~~ Photovoltaic reference devices – Procedures for establishing calibration traceability

1 Scope ~~and object~~

This part of IEC 60904 sets the requirements for calibration procedures intended to establish the traceability of photovoltaic (PV) reference ~~solar~~ devices to SI units as required by IEC 60904-2.

This document applies to ~~photovoltaic (~~PV~~)~~ reference ~~solar~~ devices that are used to measure the irradiance of natural or simulated sunlight for the purpose of quantifying the performance of PV devices. The use of a PV reference ~~solar~~ device is required in ~~the application of~~ many standards concerning PV (e.g. IEC 60904-1 and IEC 60904-3).

This document has been written with single-junction PV reference ~~solar~~ devices in mind, in particular crystalline silicon, but it is sufficiently general to include other single-junction technologies. ~~However, the main part of the standard is sufficiently general to include other technologies. The methods described in Annex A, however, are limited to single junction technologies.~~

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.

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-2, *Photovoltaic devices – Part 2: Requirements for ~~reference solar~~ photovoltaic reference devices*

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

~~ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*~~

~~ISO 9059, *Solar energy – Calibration of field pyrheliometers by comparison to a reference pyrheliometer*~~

~~ISO 9846, *Solar energy – Calibration of a pyranometer using a pyrheliometer*~~

ISO/IEC Guide 98-3: 2008, *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 terms and definitions given in IEC TS 61836 and the following apply.

NOTE The different reference instruments for the traceability chain of solar irradiance are defined in this clause. ~~Table 1 lists and compares them with those in use for time. Figure 1 shows schematically the most common traceability chains, based on the methods described in Annex A.~~ Typical examples for each category are listed in Table 1, which also refers to relevant standards (where available). Figure 1 then shows schematically the most common traceability chains linking these instruments and the relevant standards (where available). Methods for the implementation of this document are described in Annex A.

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

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
primary standard
~~a device, which implements physically one of the SI units or directly related quantities.~~

standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity

Note 1 to entry: The concept of a primary standard is equally valid for base quantities and derived quantities.

Note 2 to entry: A primary standard is never used directly for measurement other than for comparison with other primary standards or secondary standards.

Note 3 to entry: Primary standards are usually maintained by national metrology institutes (NMIs) or similar organizations entrusted with maintenance of standards for physical quantities. Often referred to also just as the «primary», the physical implementation is selected such that long-term stability, ~~precision~~ accuracy and repeatability of measurement of the quantity it represents are guaranteed to the maximum extent possible by current technology.

Note 4 to entry: The World Radiometric Reference (WRR) as realized by the World Standard Group (WSG) of cavity radiometers is the accepted primary standard for the measurement of solar irradiance.

3.2
secondary standard
device which, by periodical comparison with a primary standard, serves to maintain conformity to SI units at other places than that of the primary standard

Note 1 to entry: A secondary standard does not necessarily use the same technical principles as the primary standard, but strives to achieve similar long-term stability, ~~precision~~ accuracy and repeatability.

Note 2 to entry: Typical secondary standards for solar irradiance are cavity radiometers which participate periodically (normally every 5 years) in the International Pyrheliometer Comparison (IPC) with the WSG, thereby giving traceability to WRR. Direct traceability to SI radiometric scale can also be available for these instruments.

3.3
primary reference
~~the reference~~ instrument which a laboratory uses to calibrate secondary references~~. It is~~, compared at periodic intervals to a secondary standard

Note 1 to entry: Often primary references can be realized at much lower costs than secondary standards.

Note 2 to entry: Typically, a ~~solar~~ PV cell is used as a reference ~~solar~~ device for the measurement of natural or simulated solar irradiance. Primary references are normally used by calibration and testing laboratories.

3.4
secondary reference
measurement device in use for daily routine measurements or to calibrate working references, calibrated at periodic intervals ~~to~~ against a primary reference

Note 1 to entry: The most common secondary references for the measurement of natural or simulated solar irradiance are ~~solar~~ PV cells and ~~solar~~ PV modules. Secondary references are normally used by calibration and testing laboratories, but sometimes also in industrial production.

3.5
working reference
measurement device in use for daily routine measurements, calibrated at periodic intervals against a secondary reference

Note 1 to entry: The most common working references for the measurement of natural or simulated solar irradiance are PV cells and PV modules.

Note 2 to entry: Working references are normally used in industrial production.

3.6
traceability
<of a PV reference device> requirement for any PV reference ~~solar~~ device, to tie its calibration value to SI units in an unbroken and documented chain of calibration transfers including stated uncertainties

Note 1 to entry: ~~The WRR has been compared twice to the SI radiometric scale and shown to be within their mutual uncertainty levels. Therefore traceability to WRR automatically provides traceability to SI units. However, the uncertainty of the ratio WRR/SI units needs to be taken into account. The World Radiation Center (WRC) recommends a rectangular uncertainty distribution with 0,3 % half-width. A third comparison is currently underway and should be published in the future.~~

~~J. Romero, N.P. Fox, C. Fröhlich *metrologia* **28** (1991) 125-8~~

~~J. Romero, N.P. Fox, C. Fröhlich *metrologia* **32** (1995/1996) 523-4~~

The WRR has been compared several times to the SI radiometric scale. While in previous comparisons the two scales were found to be indistinguishable within the uncertainty of the comparison, the latest comparison of scales established that there is a systematic shift between the scales, with WRR reading 0,34 % higher irradiance than the SI scale. The uncertainty of this shift was given as 0,18 % (k = 2). Therefore, traceability to WRR automatically provides traceability to SI units. However, the shift between the scales may be corrected for those measurements traceable to the WRR. The uncertainty of the scale comparison shall be included into the uncertainty budget. Essentially there are two possibilities for those measurements traceable to SI units via the WRR. Firstly, no correction is applied for the scale difference and a larger uncertainty of 0,3 % (rectangular distribution) shall be used. Secondly an explicit correction of the scale difference amounting to 0,34 %. In this case the uncertainty contribution is 0,18 % (k = 2). The value of 0,34 % for the scale difference is the latest available at time of publication of this document. The scientific literature should be checked for possible updates of this difference and its uncertainty. In particular, it is possible that in the future the WRR is adapted to take account of this difference and bring it into line with SI units. In this case no further correction shall be applied.

[SOURCE: A Fehlmann, G Kopp, W Schmutz, R Winkler, W Finsterle, N Fox, *metrologia* **49** (2012) S34]

Table 1 – Examples of reference instruments used in a traceability chain of ~~time and~~ solar irradiance

Reference instrument	~~Time~~	Solar irradiance
Primary standard	~~Cesium atomic clock at National Metrology Institute (NMI)~~	Group of cavity radiometers constituting the World Standard Group (WSG) of the World Radiometric Reference (WRR) Cryogenic trap detector Standard lamp
Secondary standard	~~Cesium atomic clock on GPS (Global Positioning System) satellites~~	Commercially available cavity radiometers compared regularly (normally every 5 years) at the International Pyrheliometer Comparison (IPC) Standard detector calibrated against a trap detector Spectroradiometer calibrated against a standard lamp
Primary reference	~~GPS receiver, set to show time~~	Normal incidence pyrheliometer (NIP) (ISO 9059) ~~Reference solar~~ PV reference device (IEC 60904-2 and IEC 60904-4)
Secondary reference	~~Quartz watch~~	Pyranometer (ISO 9846) ~~Reference solar~~ PV reference device (IEC 60904-2)
Working reference		Pyranometer (ISO 9847) PV reference device (IEC 60904-2)

~~NOTE Direct traceability of absolute radiometers to SI radiometric scale may also be available.~~

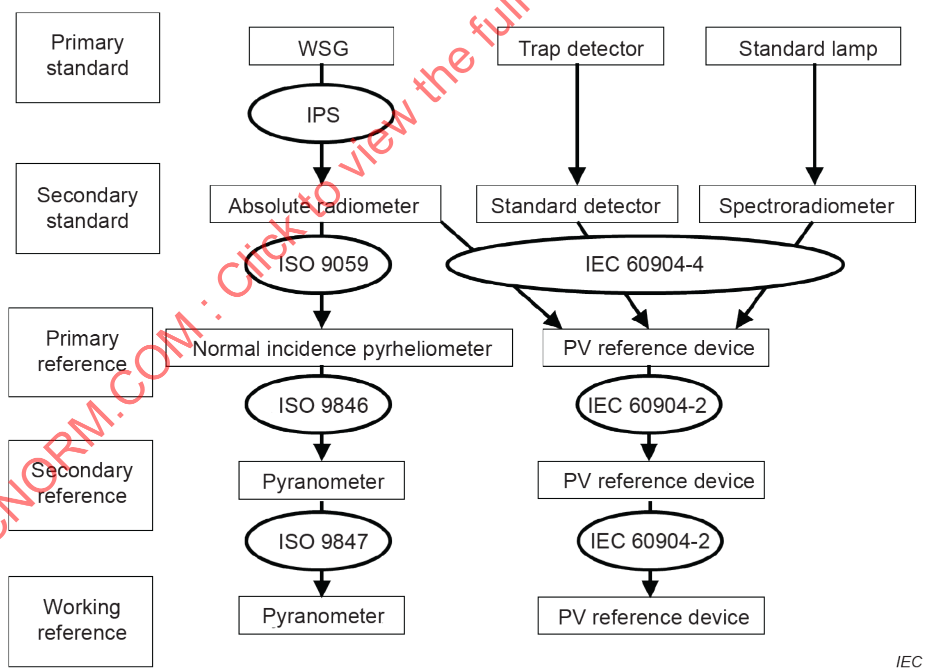

Figure 1 – Schematic of most common reference instruments and transfer methods used in the traceability chains for solar irradiance detectors

4 Requirements for traceable calibration procedures of PV reference ~~solar~~ devices

A traceable calibration procedure is necessary to transfer calibration from a standard or reference measuring solar irradiance and based on a physical principle other than PV effect (such as cavity radiometer, pyrheliometer and pyranometer) to a PV reference ~~solar~~ device. The requirements for such procedures are as follows:

a) Any measurement instrument required and used in the transfer procedure shall be an instrument with an unbroken traceability chain.

b) A documented uncertainty analysis.

c) Documented repeatability, such as measurement results of laboratory intercomparison, or documents of laboratory quality control.

d) Inherent absolute ~~precision~~ accuracy, given by a limited number of intermediate transfers.

~~NOTE 1~~ Normally the transfer would be from a secondary standard to a PV reference ~~solar cell~~ device constituting a primary reference.

~~NOTE 2~~ The transfer from one PV reference ~~solar~~ device to another is covered by IEC 60904-2.

5 Uncertainty analysis

An uncertainty estimate according to ~~MISC UNCERT ED. 1.0 (1995-01)~~ ISO/IEC Guide 98-3: 2008 shall be provided for each traceable calibration procedure. This estimate shall provide information on the uncertainty of the calibration procedure and quantitative data on the following uncertainty factors for each instrument used in performing the calibration procedure. In particular:

a) Component of uncertainty arising from random effects (Type A).

b) Component of uncertainty arising from systematic effects (Type B).

~~Nevertheless~~ A full uncertainty analysis has to be performed for the implementation of the calibration method by a particular laboratory. Annex A provides examples of the main uncertainty components in some particular implementations. Due to the variety of methods available, it is impossible to give a detailed guidance on how a particular uncertainty analysis should be made. However, the following components shall be considered:

– uncertainty of all measurement instruments involved;
– offset and drift of all measurement instruments;
– uncertainty of all references used;
– uncertainty of measured device temperature;
– uncertainty introduced of deviations between actual and nominal device temperature;
– uncertainty of irradiance measurement (total and spectral irradiance);
– uncertainty introduced by deviations between actual and reference spectral irradiance;
– contributions due to repeatability and reproducibility;
– uncertainty due to instability of conditions and instruments.

6 Calibration report

The calibration report shall ~~conform to the requirements of ISO/IEC 17025 and shall normally~~ include at least the following information:

a) title (e.g. ”Calibration Certificate”);

b) name and address of laboratory, and location where the ~~tests and/or~~ calibrations were carried out, if different from the address of the laboratory;

c) unique identification of the report (such as serial number) and of each page, the total number of pages and the date of issue;

d) name and address of the client placing the order;

e) description and unambiguous identification of the item(s) ~~tested or~~ calibrated;

f) date of receipt of calibration item(s) and date(s) of performance of ~~test or~~ calibration, as appropriate;

g) calibration results and their uncertainties, including the temperature of the device at which the calibration was performed;

h) reference to sampling procedures used by the laboratory where these are relevant to the validity or application of the results;

i) the name(s), title(s) and signature(s) or equivalent identification of person(s) authorizing the report;

j) where relevant, a statement to the effect that the results relate only to the items ~~tested or~~ calibrated;

k) where relevant the spectral responsivity of the PV reference device;

l) where relevant the temperature coefficient of the PV reference device.

7 Marking

The calibrated PV reference ~~solar~~ device shall be marked with a serial number or reference number and the following information attached or provided on an accompanying certificate:

a) date of (actual or present) calibration;

b) calibration value and its ~~temperature coefficient (if applicable)~~ uncertainty;

c) identification of laboratory having performed the calibration.

Annex A
(informative)

Examples of validated calibration procedures

A.1 General

A.1.1 Overview

Annex A describes examples of calibration procedures for PV reference ~~solar cells~~ devices as primary reference devices, together with their stated uncertainties. These procedures serve to establish the traceability of PV reference ~~solar~~ devices to SI units as required by IEC 60904-2. Primary reference devices calibrated in accordance with these procedures serve to establish the traceability of further PV reference ~~solar~~ devices, which then constitute secondary reference devices.

As already mentioned in Clause 1, the methods in this annex are limited to PV single junction technology. Moreover, they have currently only been validated for crystalline silicon technology, although they ~~should~~ could be applicable to other technologies.

The methods have been implemented in various laboratories around the world and validated in international intercomparisons, most notably the World Photovoltaic Scale (WPVS). However, the description in this document is more generalized. For details of the various implementations, the references in peer-reviewed publications are given at the end of each procedure.

The uncertainty estimates are based on U_{95} (coverage factor k = 2) for all single components. The combined expanded uncertainty is calculated as the square root of the sum of squares of all components. The uncertainties provided are simplified versions (restricted to the main components) as provided by the laboratories having implemented the procedure. These uncertainty calculations only serve as guidelines and will have to be adapted to the particular implementation of each procedure in a given laboratory. The uncertainties achieved by any implementation of these methods might be considerably different. Uncertainties quoted by a given laboratory have to be based on an explicit specific analysis and cannot be taken by reference to the uncertainty estimates in this document.

A.1.2 Examples of validated methods

A.2 Global sunlight method (GSM)

A.3 Differential spectral responsivity calibration (DSR)

A.4 Solar simulator method (SSM)

A.5 Direct sunlight method (DSM)

A.1.3 List of common symbols

I_{SC}	short-circuit current of PV reference ~~cell~~ device
T_j	temperature of PV reference ~~cell~~ device
M_G	irradiance correction factor (see below)
M_T	temperature correction factor (see below)
T_{coef}	temperature coefficient α of the short-circuit current (IEC 60891) normalized to the short-circuit current at 25 °C and expressed in 1/ ~~°C~~ K
~~MMF~~	~~mismatch factor (see below)~~
SMM	spectral mismatch factor (IEC 60904-7)
λ	wavelength
~~$S(\lambda)$~~	~~spectral response of reference cell~~

~~$s(\lambda)$ differential spectral responsivity of reference cell~~

$s(\lambda)$ spectral responsivity of PV reference device as a function of wavelength λ

$s(\lambda,T_j)$ spectral responsivity of PV reference device as a function of wavelength λ and temperature T_j

$\frac{\partial s(\lambda,T_j)}{\partial T}$ partial derivative of spectral responsivity with respect to temperature as a function of wavelength λ

$\tilde{s}(\lambda)$ differential spectral responsivity of PV reference device

~~E_m~~ $E_{meas}(\lambda)$ spectral irradiance distribution of natural or simulated sunlight

~~E_s~~ $E_{ref}(\lambda)$ standard or reference spectral irradiance distribution according to IEC 60904-3

G_{dir} direct irradiance

G_{dif} diffuse in-plane irradiance

G_T total in-plane irradiance

~~E_{STC}~~ G_{STC} irradiance at STC (= 1 000 Wm–2)

CV calibration value, i.e. I_{SC} at STC

AM air mass

STC standard test conditions (1 000 Wm^{-2}, 25 °C and ~~$E_s(\lambda)$~~ $E_{ref}(\lambda)$)

P local air pressure

P_0 101 300 Pa

θ solar elevation angle

A.1.4 Common formulae

The methods described in Clauses A.2, A.4 and A.5 have some common calculations, which are detailed in A.1.4. Details of the various implementations are then described in each subclause.

~~The I_{SC} is normally not measured at exactly 1 000 Wm^{-2}, but at an irradiance level close to it. Under the assumption that the I_{SC} of the reference cell varies linearly with irradiance, the following correction is made:~~

$$I_{SC}(1000\ \text{Wm}^{-2}) = I_{SC} M_G = I_{SC} \frac{1000 \frac{\text{W}}{\text{m}^2}}{G_T} \qquad \text{(A.1)}$$

~~STC mandate a device temperature of 25 °C, but measurements will not always be taken at this temperature. The deviations in temperature should be accounted for in the uncertainty budget. It is also possible to correct I_{SC} from the measurement temperature T_j to 25 °C by multiplying with the temperature correction factor M_T defined by~~

$$I_{SC}(25\,°\text{C}) = I_{SC}(T_j) M_T = \frac{I_{SC}(T_j)}{1 - T_{coef}(25\,°\text{C} - T_j)} \qquad \text{(A.2)}$$

~~The correction for the difference in spectral sensitivity of the reference cell to be calibrated and the device used to measure the irradiance can be described as a MMF~~

~~$$MMF = \frac{\int_{300\,\text{nm}}^{4000\,\text{nm}} S(\lambda)\cdot E_s(\lambda)\cdot d\lambda}{\int_{300\,\text{nm}}^{4000\,\text{nm}} S(\lambda)\cdot E_m(\lambda)\cdot d\lambda} \frac{\int_{300\,\text{nm}}^{4000\,\text{nm}} E_m(\lambda)\cdot d\lambda}{\int_{300\,\text{nm}}^{4000\,\text{nm}} E_s(\lambda)\cdot d\lambda} \qquad \text{(A.3)}$$~~

~~NOTE The integration range is taken based on the definition of $E_s(\lambda)$. If the measurement range, in particular that of $E_m(\lambda)$, does not cover this entire range, suitable approximation, extrapolation or modelling can be used, but needs to be accounted for in the uncertainty calculation.~~

~~The calibration value CV of the reference cell is then calculated as~~

~~$$CV = I_{SC} M_G M_T MMF \qquad \text{(A.4)}$$~~

The I_{SC} is normally not measured at exactly 1 000 Wm^{-2}, but at an irradiance level close to it. Under the assumption that the I_{SC} of the PV reference device varies linearly with irradiance according to IEC 60904-10, the following correction is made:

$$I_{SC}\left(G_{STC}\right) = I_{SC} M_G = I_{SC}\frac{G_{STC}}{G_T} \qquad \text{(A.1)}$$

If the irradiance measurement is traceable to the WRR, then the irradiance reading may be corrected for the scale difference to SI units.

STC mandate a device temperature of 25 °C, but measurements will not always be taken at this temperature. The deviations in temperature should be accounted for in the uncertainty budget. It is also possible to correct I_{SC} from the measurement temperature T_j to 25 °C by multiplying with the temperature correction factor M_T defined by:

$$I_{SC}\left(25\,°C\right) = I_{SC}\left(T_j\right) M_T = \frac{I_{SC}\left(T_j\right)}{1 - T_{coef}\left(25\,°C - T_j\right)} \qquad \text{(A.2)}$$

The correction for the difference in spectral responsivity of the PV reference device to be calibrated and the device used to measure the irradiance can be calculated as a spectral mismatch SMM:

$$SMM = \frac{\int_0^{\infty} E_{ref}(\lambda)\,d\lambda}{\int_0^{\infty} E_{meas}(\lambda)\,d\lambda} \frac{\int_0^{\infty} E_{meas}(\lambda)\,s(\lambda)\,d\lambda}{\int_0^{\infty} E_{ref}(\lambda)\,s(\lambda)\,d\lambda} \qquad \text{(A.3)}$$

NOTE Formula A.3 is the same formula as in IEC 60904-7 for the case of a thermopile detector where the spectral responsivity of the device under test is now the spectral responsivity of the PV reference device to be calibrated.

The integration range is over all wavelengths. For $E_{ref}(\lambda)$ the irradiance is zero below 280 nm. This also holds normally for $E_{meas}(\lambda)$ in particular under natural sunlight. For practical reasons the explicit integral cannot be calculated above 4 000 nm, as $E_{ref}(\lambda)$ is not defined explicitly but only the integral irradiance between 4 000 nm and infinity. $E_{meas}(\lambda)$ is typically only measured for an even smaller wavelength range, for example up to 2 500 nm. In order to calculate the integrals, suitable approximation (truncation of the integrals) or extension of measured spectral irradiance data by extrapolation or modelling can be used, but has to be accounted for in the uncertainty calculation. For example, the truncation of the integrals at 4 000 nm for the DSM will lead to an error of 0,025 %, whereas truncation at 2 500 nm to an error of 0,116 %. These values have been determined from the direct and global spectral irradiance as defined in IEC 60904-3.

Cavity radiometers used for irradiance measurement are assumed to detect irradiance at all wavelengths perfectly. Possible deviations from such a perfect characteristic should be corrected or accounted for in the measurement uncertainty.

The calibration value (CV) of the PV reference device is then calculated as:

$$CV = I_{SC} \frac{M_G M_T}{SMM} \tag{A.4}$$

A.1.5 Reference documents

- IEC 60891: *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*
- IEC 60904-7: *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*
- IEC 60904-10: *Photovoltaic devices – Part 10: Methods of linearity measurements*
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A.2 Global sunlight method (GSM)

A.2.1 General

The establishment of traceability is based on the calibration using the continuous sun-and-shade method as described in ISO 9846. The PV reference ~~solar cell~~ device to be calibrated is compared under natural sunlight with two reference radiometers, namely a pyrheliometer measuring direct solar irradiance and a pyranometer measuring diffuse solar irradiance by application of a continuous ~~shade~~ shading device under normal incidence conditions. The total solar irradiance is determined by the sum of direct irradiance and diffuse in-plane irradiance. As a pyrheliometer, a secondary standard is used in the form of an absolute cavity radiometer regularly compared ~~at 5-year intervals~~ with the World Standard Group (WSG) establishing the World Radiometric Reference (WRR). The calibration factor for the ~~photovoltaic~~ PV reference ~~cell~~ device is determined from the measured short-circuit current, ~~scaled to 1 000 W/m² and corrected for spectral mismatch (IEC 60904-7)~~ corrected according to Formula (A.4) based on the measured spectral irradiance of the global sunlight and the relative spectral ~~response~~ responsivity of the PV reference ~~solar cell~~ device to be calibrated.

Under certain conditions the simplified global sunlight method is applicable. The short-circuit current of the PV reference ~~cell~~ device is ~~scaled to 1 000 W/m²~~ corrected by Formulae (A.1) and (A.2) and then plotted versus pressure corrected geometric air mass (AM). The calibration value is determined from a linear least square fit at AM = 1,5. A ~~spectral mismatch~~ correction according to Formula (A.3) is not required and hence the measurements of the spectral irradiance of the natural sunlight and the spectral ~~response~~ responsivity of the PV reference device are not necessary. In the simplified version of the global sunlight method ~~no explicit spectral mismatch correction is performed and it~~ the explicit correction according to Formula (A.3) is replaced by conditions which should ensure that the spectral irradiance of the natural sunlight is sufficiently close to the defined standard spectral irradiance (IEC 60904-3) that the uncertainty component is smaller than quoted in Table A.1. Although this should be ensured by the conditions listed in the description of the method below, it should be explicitly verified (preferentially by using the full global sunlight method). After this validation the simplified version can be applied as long as the boundary conditions are the same as during the validation.

~~NOTE 1~~ The verification and validation will produce numerical values for both methods. If the agreement between these numerical values is within the uncertainty budget of the methods, the simplified method shall be deemed validated.

~~NOTE 2~~ The simplified procedure gives accurate results for devices with a spectral ~~response~~ responsivity over a broad range of the solar spectrum for example crystalline silicon devices~~,~~ but significant errors may be introduced for narrow spectral ~~response~~ responsivity devices.

A.2.2 Equipment

a) A mounting platform, which can be oriented normal to the sun within an accuracy of ±0,5° throughout the calibration run.

b) A cavity radiometer, traceable to the WRR.

c) A pyranometer, traceable to the WRR.

d) A shading device to provide shade to item c). The field angle, viewing angle and aperture angle provided by the shade shall compensate the respective descriptive angles of the cavity radiometer of item b).

e) A temperature controlled mounting block for the PV reference device under test capable of maintaining the ~~cell~~ device temperature at (25 ± 2) °C throughout all calibration runs if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval.

f) Traceable means to measure the short-circuit current of the ~~solar cell~~ PV reference device to an accuracy of ±0,1 % or better.

g) Traceable means to measure the signal of the pyranometer to an accuracy of ±0,5 % or better.

h) Not required in simplified version: A spectroradiometer capable of measuring the spectral irradiance of the total in-plane natural sunlight ~~in the wavelength range of 350 – 2 500 nm (or larger)~~.

~~NOTE 1 Not required in simplified version.~~

i) Not required in simplified version: Apparatus to determine the relative spectral ~~response~~ responsivity of the PV reference ~~solar cell~~ device according to IEC 60904-8.

~~NOTE 2 Not required in simplified version.~~

j) Only required in simplified version: Means to measure the sun's elevation to ~~a precision~~ an accuracy of ±2°. Alternatively, the elevation of the sun during the data sampling can be taken from almanacs or computed, as long as the ~~precision~~ accuracy requirement is met for the instant of data sampling. The latter normally requires traceable means to measure time for the computation of air mass.

~~NOTE 3 Only required in simplified version.~~

k) Only required in simplified version: A manometer to measure the local air pressure P to an accuracy of ±250 Pa or better.

~~NOTE 4 Only required in simplified version.~~

A.2.3 Measurements

A calibration according to this document shall be performed only on clear, sunny days with no visible cloud cover within 30° of the sun.

a) Not required in simplified version: Determine the relative spectral ~~response~~ responsivity of the PV reference ~~cell~~ device to be calibrated according to IEC 60904-8.

~~NOTE 1 Not required in simplified version.~~

b) Select the site and/or the season of the year to ensure that the sun's elevation reaches an angle during the course of the day which corresponds to AM = 1,5 (41,8° at P_0).

c) Mount the cavity radiometer on the sun-pointing device (item A.2.2.a). Commercially available radiometers have their own electronic unit which shall be connected to the instrument following the manufacturer's recommendations. Allow sufficient time to stabilize the electronic unit.

d) Mount the PV reference ~~solar cell~~ device to be calibrated coplanar on the mounting platform, attaching it to the mounting block and maintain the ~~cell~~ device temperature at (25 ± 2) °C throughout all calibration runs if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval.

e) Mount the pyranometer intended to measure diffuse solar irradiance coplanar on the mounting platform. Ensure that within the field of view of the pyranometer no reflective surfaces ~~may~~ influence the measurement result. Mount the shading device and ensure that the sensitive area of the pyranometer is pointed to the centre of the shade.

f) Not required in simplified version: Mount the spectroradiometer coplanar on the mounting platform.

~~NOTE 2 Not required in simplified version.~~

g) Take simultaneous readings according to the following steps:

   1) Ensure the alignment of all instruments with respect to the sun and the proper alignment of the shading device.

   2) Ensure that the temperature of the PV reference ~~solar cell~~ device is within the limits given in d).

   3) Record G_{dir}, the direct normal irradiance as indicated by the cavity radiometer.

   4) Record G_{dif}, the diffuse in-plane irradiance as indicated by the pyranometer.

   5) Record I_{SC}, the short-circuit current of the PV reference ~~solar cell~~ device to be calibrated.

   6) Not required in simplified version: Record ~~$E(\lambda)$~~ $E_{meas}(\lambda)$, the spectral irradiance of the global natural sunlight.

~~NOTE 3 Not required in simplified version.~~

   7) Only required in simplified version: Measure θ, the solar elevation angle, or alternatively, record the hour, minute and second of the data sampling and calculate the sun's elevation.

~~NOTE 4 Only required in simplified version.~~

   8) Only required in simplified version: Record P, the local air pressure.

~~NOTE 5 Only required in simplified version.~~

   9) Not required in simplified version: Repeat Steps 1 to 6 several times.

~~NOTE 6 Not required in simplified version.~~

   10) Only required in simplified version: Repeat steps 1 to 5, 7 and 8 at least every 5 min for several hours before and after solar noon, spanning the range of air mass from AM < 1,5 to AM > 3,0 in both time periods.

~~NOTE 7 Only required in simplified version.~~

h) Repeat the whole measurement procedure on at least two other days.

A.2.4 Data analysis

For all data points taken, apply in sequence the following steps:

a) Reject data points where G_{dir}, G_{dif} or I_{sc} deviate by more than ±3 % when compared to the previous data point.

b) Calculate the total irradiance $G_T = G_{dir} + G_{dif}$.

c) Scale the measured short-circuit current I_{sc} of the PV reference ~~solar cell~~ device to be calibrated to ~~1000 W/m²~~ G_{STC} according to Formula (A.1).

d) Correct for temperature according to Formula (A.2).

NOTE ~~1~~ This is normally not required as the temperature is maintained as described in A.2.3.d) and the allowed temperature deviation is accounted for in the uncertainty budget.

e) Correct for differences in spectral ~~mismatch~~ responsivity according to Formula (A.3), where ~~E_m~~ $E_{meas}(\lambda)$ is the measured spectral irradiance of the global natural sunlight.

f) Calculate the calibration value according to Formula (A.4).

g) Average all calibration values for one day to obtain CV_1.

h) Repeat steps a) to g) for the other days of measurement runs to obtain CV_2, CV_3, .. CV_n accordingly.

i) Determine the arithmetic average of all n CV_i values analysed according to the above steps which yields the final calibration value for the PV reference device:

~~$CV = (CV_1 + CV_2 + ... + CV_n) / n$. (A.5)~~

$$CV = \frac{\sum_{i=1}^{n} CV_i}{n} \qquad \text{(A.5)}$$

j) In the simplified version steps e) to g) are replaced as follows:

1) Reject data points for which the ratio G_{dif}/G_T is either smaller than 0,1 or larger than 0,3. Also reject data points where G_T is outside the range ~~800 – 1 200 W/m²~~ G_{STC} ±20 %.

NOTE ~~2~~ This is to ensure that data used for the analysis are taken during atmospheric conditions close to the standard reference spectrum.

2) Using the sun's elevation angle and the atmospheric pressure, calculate the air mass (AM) at the moment of measurement according to:

$$AM = \frac{P}{P_0 \sin\theta} \qquad \text{(A.6)}$$

3) Reject all data samples where $AM > 3$.

4) Plot the value of I_{sc} obtained after step d) versus the air mass value AM_i of each corresponding measurement sample.

5) By using a linear ~~least-square technique~~ least-squares fit, calculate the slope (m) and offset (b) of the best fit straight line of the data set. In order to balance the fit, all short-circuit current readings should be averaged for AM bins of 0,01 before performing the fit. Both morning and afternoon have to contribute at least 33 % of the total number of measurement samples used for the least-squares fit.

NOTE ~~3~~ For a good straight line fit, 10 data points shall be considered as minimum. The more data points in the least-squares fit are close to $AM = 1{,}5$, the smaller the uncertainty of the procedure.

NOTE ~~4~~ It is permissible to use only data from half a day (morning or afternoon). However, in the final average, at least data from three different days with at least two mornings and two afternoons have to be included.

6) Calculate the calibration value of the PV reference device by the formula:

$$CV_1 = m \times AM + b \quad \text{with } AM = 1{,}5 \qquad \text{(A.7)}$$

7) Perform steps h) and i).

A.2.5 Uncertainty estimates

In Table A.1, typical values of the uncertainty components for the global sunlight method (left column) and its simplified version (right column) are listed, resulting in combined expanded uncertainties U_{95} (with coverage factor k = 2) of ~~0,8 % and 1,1 %~~ 0,7 % and 0,8 % respectively.

Table A.1 – Typical uncertainty components (k = 2) of global sunlight method

~~**Uncertainty in measurement of short circuit current**~~	~~**0,1 %**~~	
~~**Uncertainty due to unstable cell temperature (± 2 K)**~~	~~**0,1 %**~~	
~~Uncertainty of direct irradiance~~	~~0,4 %~~	
~~Uncertainty of diffuse irradiance~~	~~1,6 %~~	
~~**Uncertainty of total irradiance (80 % direct and 20 % diffuse)**~~	~~**0,6 %**~~	
~~**Uncertainties due to spectral mismatch correction (IEC 60904-7) or spectral irradiance deviations between test conditions and the reference spectral irradiance of AM 1,5 (IEC 60904-3)**~~	~~**0,3 %**~~	~~**0,4 %**~~
~~**Variations of data on different days**~~	~~**0,3 %**~~	~~**0,8 %**~~
~~**Combined expanded uncertainty**~~	~~**0,8 %**~~	~~**1,1 %**~~

Uncertainty in measurement of short-circuit current	< 0,1 %	
Uncertainty due to unstable device temperature (±2 K)	< 0,1 %	
Uncertainty of direct irradiance	< 0,25 %	
Uncertainty of diffuse irradiance	< 1,6 %	
Uncertainty of total irradiance (80 % direct and 20 % diffuse)	< 0,5 %	
Uncertainty of scale difference WRR versus SI	0,18 %	
Uncertainties due to correction with Formula A.3 or spectral irradiance deviations between test conditions and the reference spectral irradiance of AM1.5G (IEC 60904-3)	0,4 %	0,5 %
Combined expanded uncertainty	< 0,7 %	< 0,8 %

A.2.6 Reference documents

– IEC 60904-8: *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

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A.3 Differential spectral responsivity calibration (DSR ~~calibration~~)

A.3.1 General

Traceability is based on a calibration of spectral responsivity based on standard detectors directly traceable to SI units. The calibration value is computed from the measured absolute spectral responsivity of the PV reference ~~cell~~ device and the reference solar spectral irradiance distribution. The spectral responsivity calibration is transferred from the standard detector irradiance level to the solar irradiance level over many orders of magnitude with no restrictions to the ~~solar cell~~ PV reference device concerning linearity or spectral match.

A.3.2 Equipment

The following apparatus is required (see Figure A.1 and Figure A.2).

a) A monochromator producing chopped spectral irradiance ~~of at least 1 mWm^{-2} nm^{-1}~~ within the wavelength range covering the spectral irradiance responsivity of the PV reference ~~solar cell~~ device to be calibrated, with a traceable wavelength setting.

b) Lamp(s) with lens or mirror entrance optics (recommended are quartz-halogen lamps to cover wavelengths above 400 nm; and xenon-arc lamps for wavelengths below 400 nm). Alternatively, a tuneable or white light cw-laser source with a continuously available spectral range covering the spectral irradiance responsivity of the PV reference device to be calibrated.

c) A bias light source, meeting in spectral irradiance, uniformity and temporal stability the requirements of class CBA as defined in IEC 60904-9.

d) A chopped monochromatic beam, traceable in its wavelength calibration, for the absolute calibration at one or more discrete wavelengths. The non-uniformity shall be smaller than ±3 % within the active area of the device to be calibrated.

   Comment: The monochromatic beam from A.3.2.a) can be used for this purpose if it fulfils the given requirement.

e) A monitor photodiode large enough to monitor the radiation power of the monochromatic beam of a) and d).

f) Optional: a standard spectroradiometer to monitor the wavelength of the monochromatic beam.

g) Standard ~~radiation~~ spectral irradiance detector(s) with temperature control directly traceable to SI units. These detectors shall be ~~of~~ photodiodes with the best available linearity, uniformity and stability.

h) Adjustable aperture (imaged onto the PV reference ~~cell~~ device);

i) Means for maintaining the temperature of the PV reference ~~cell~~ device at ~~(25 ± 2)~~ (25 ± 0,5)°C.

j) Means for measuring the AC short-circuit currents of the PV reference ~~cell~~ device, the standard detector(s) and the monitoring detector, for example with a lock-in amplifier. The variation of the amplification factor of such amplifiers shall be less than 0,1 % over the signal ranges used. Preferably the same amplifier and measurement range is used for the PV reference ~~cell~~ device and the standard detector.

k) Means for measuring the DC component of the PV reference ~~cell~~ device I_b as defined in step A.3.3.f).

A.3.3 Test procedure

a) Set and maintain the temperature of the PV reference ~~cell~~ device to (25 ± 0,2) °C. If larger temperature deviations occur, corrections have to be applied using the spectral temperature coefficient of the spectral irradiance responsivity.

b) Adjust the aperture until its image ~~coincides with the active area of the reference cell within ± 1 mm~~ over-illuminates the whole PV reference device.

c) Mount the standard detector ~~in a position close to the focus of the monochromatic beam collecting the whole radiation power~~ at the same position and plane where the PV reference device is calibrated.

d) Calibrate the monochromatic irradiance source of A.3.2.a) (without bias radiation) with respect to its relative spectral irradiance. Use ~~its~~ the chopped monochromatic beam to determine the ratio of the AC short-circuit currents of the monitor photodiode ~~($\Delta I_{mon,cal}$)~~ $(\Delta I_{mon,st}(\lambda))$ and standard detector ~~(ΔI_{st})~~ $(\Delta I_{st}(\lambda))$ which are measured simultaneously at wavelength intervals of not more than 10 nm over the whole responsivity range.

e) Set the white bias irradiance E_b to the desired operational level (between 10 Wm^{-2} and ~~1 100~~ 1 500 Wm^{-2}) and measure the corresponding DC short-circuit current $I_b = I_{sc}(E_b)$ of the PV reference device. Ensure that the standard detector is protected from the white bias irradiance.

f) Measure the relative differential spectral irradiance responsivity of the PV reference ~~cell~~ device by using the chopped monochromatic radiation of irradiance source A.3.2.a) and determining the ratio of the short-circuit currents of PV reference ~~cell~~ device ~~(ΔI_{ref})~~ $(\Delta I_{ref}(\lambda, I_b))$ and monitor photodiode ~~(ΔI_{mon})~~ $(\Delta I_{mon,ref}(\lambda))$. Calculate the relative differential spectral irradiance responsivity $\tilde{s}(\lambda, I_b)_{rel}$ ~~$s(\lambda, I_b)_{rel}$~~ of the PV reference ~~cell~~ device under bias irradiance E_b:

$$\cancel{s(\lambda, I_b)_{rel} = \frac{\Delta I_{ref}}{\Delta I_{mon}} \cdot \frac{\Delta I_{mon,cal}}{\Delta I_{st}} \cdot S_{st}(\lambda)} \qquad \cancel{(A.8)}$$

$$\tilde{s}(\lambda, I_b)_{rel} = \frac{\Delta I_{ref}(\lambda, I_b)}{\Delta I_{mon,ref}(\lambda)} \frac{\Delta I_{mon,st}(\lambda)}{\Delta I_{st}(\lambda)} s_{st}(\lambda) \qquad (A.8)$$

where $s_{st}(\lambda)$ is the spectral irradiance responsivity of the standard detector at wavelength λ.

– Comment: If a standard spectroradiometer for wavelength monitoring or correction is used (A.3.2.f) a wavelength correction shall be performed prior to the determination of $\tilde{s}(\lambda, I_b)_{rel}$.

g) Repeat steps e) and f) at five or more different bias levels covering at least the range between 10 Wm^{-2} and 1 100 Wm^{-2}, thus including a linearity test of relative spectral irradiance responsivity.

h) Calibrate the monochromatic irradiance source of A.3.2.d) (possibly in a different measurement plane with better uniformity) at one to three wavelengths λ_i (without bias radiation) with respect to its absolute spectral irradiance. Use the chopped monochromatic beam to determine the ratio of the AC short-circuit currents of the monitor photodiode $(\Delta I_{mon,st}(\lambda_i))$ and standard detector $(\Delta I_{st}(\lambda_i))$ which are measured simultaneously.

~~i) With the bias irradiance set as in step f) to a low level near to or at the minimum as specified in step h), measure the absolute differential spectral responsivity of the reference cell at the 3 wavelengths of the narrowband filter set and the DC short circuit~~

~~current $I_0 = I_{sc}(E_0)$. This is done by using the chopped and filtered monochromatic radiation as described in item A.3.1.d).~~

i) Set the white bias irradiance to a low level E_0 near to or at the minimum as specified in step e) and measure the corresponding DC short-circuit current $I_0 = I_{sc}(E_0)$ of the PV reference device. Ensure that the standard detector is protected from the white bias irradiance.

~~j) The absolute differential spectral responsivity $s(\lambda_i, I_e)$ with i = 1, 2, 3 is determined by the ratio of short-circuit current to irradiance (as measured by the standard detector in the working plane) with each filter in turn.~~

j) Measure the absolute differential spectral irradiance responsivity of the PV reference device at one to three wavelengths λ_i by using the chopped monochromatic radiation of irradiance source in A.3.2.d) and determining the ratio of the short-circuit currents of PV reference device ($\Delta I_{\text{ref}}(\lambda_i, I_0)$) and monitor photodiode ($\Delta I_{\text{mon,ref}}(\lambda_i)$). Calculate the absolute differential spectral irradiance responsivity $\tilde{s}(\lambda_i, I_0)$ of the PV reference device under bias irradiance E_0:

$$\tilde{s}(\lambda_i, I_0) = \frac{\Delta I_{\text{ref}}(\lambda_i, I_0)}{\Delta I_{\text{mon,ref}}(\lambda_i)} \frac{\Delta I_{\text{mon,st}}(\lambda_i)}{\Delta I_{\text{st}}(\lambda_i)} s_{\text{st}(\lambda_i)} \tag{A.9}$$

where $s_{\text{st}(\lambda_i)}$ is the spectral irradiance responsivity of the standard detector at wavelength λ_i.

– Comment: If a standard spectroradiometer for wavelength monitoring or correction is used (A.3.2.f) a wavelength correction shall be performed prior to the determination of $\tilde{s}(\lambda_i, I_0)$.

– Comment: If the monochromatic beam of A.3.2.a) is used for the absolute calibration of the complete differential spectral irradiance responsivity of the PV reference device, the calibration of the monochromatic irradiance source in A.3.3.d) is performed with respect to its absolute spectral irradiance. Subsequently the absolute differential spectral irradiance responsivity of the PV reference device $\tilde{s}(\lambda, I_b)$ instead of its relative differential spectral irradiance responsivity $\tilde{s}(\lambda, I_b)_{\text{rel}}$ is obtained in step A.3.3.f) and steps A.3.3.h), A.3.3.i) and A.3.3.j) can be omitted.

A.3.4 Data analysis

~~a) Calculate the ratio $k_i(\lambda_i)$ = (relative spectral responsivity as determined in A.3.2.g)/(absolute spectral responsivity as determined in A.3.2.i.) for each of the three wavelengths λ_1, λ_2, λ_3 under the E_e irradiation.~~

~~b) Compute the absolute differential spectral responsivities by scaling the relative responsivity with the mean value of the k_i determined in step a):~~

$$\cancel{s(\lambda, I_b) = s(\lambda, I_b)_{\text{rel}} * (k_1 + k_2 + k_3)/3} \tag{A.9}$$

~~c) Compute the differential responsivity $s_{\text{AM1.5}}(I_b)$ under irradiation with $E_s(\lambda)$ for at least 5 different levels of bias light determined by I_b:~~

$$\cancel{s_{\text{AM1.5}}(I_b) = \frac{\int s(\lambda, I_b) \cdot E_s(\lambda) \cdot d\lambda}{E_{\text{STC}}}} \tag{A.10}$$

~~with~~

$$\cancel{E_{\text{STC}} = \int E_s(\lambda) d\lambda = 1000 \ \text{Wm}^{-2}} \tag{A.11}$$

~~and~~

~~$I_b = I_{sc}(E_b)$ (A.12)~~

~~d) The reference solar cell can be considered to be linear, if the variation of $s_{AM1,5}(I_b)$ over ≥ 5 successive sets of measurements at different bias light levels is less than ± 0,5 %. In this case, take the mean of $s_{AM1,5}(I_b)$ as the definitive responsivity under STC and calculate CV:~~

~~$CV = s_{AM1.5}E_{STC}$ (A.13)~~

~~e) If the reference cell is nonlinear, it shall not serve as transfer standard for the scope of this standard.~~

a) Calculate the ratio $k_i(\lambda_i)$ = (relative spectral irradiance responsivity as determined in A.3.3.f)/(absolute spectral irradiance responsivity as determined in A.3.3.j) for each of the three wavelengths λ_1, λ_2, λ_3 under the E_0 irradiation. All three $k_i(\lambda_i)$ values shall be within a range of ±0,5 % of the average of the three values, otherwise measurements shall be repeated until fulfilled. All measurement uncertainties shall be correctly assigned to the k_i values and the relative DSR. Then the uncertainties of the k_i values shall be propagated through the averaging, taking correlations into account. The combined standard uncertainty shall be larger than the standard deviation of the average of the three $k_i(\lambda_i)$ values, since the standard deviation reflects the uncorrelated measurements uncertainties and the reproducibility of the absolute differential spectral responsivity measurement.

b) Compute the absolute differential spectral responsivities by scaling the relative responsivity with the mean value of the k_i determined in step a):

$$\tilde{s}(\lambda, I_b) = \tilde{s}(\lambda, I_b)_{rel} \frac{k_1 + k_2 + k_3}{3} \quad \text{(A.10)}$$

c) Compute the differential responsivity $s_{AM1.5G}(I_b)$ under irradiation with $E_{ref}(\lambda)$ for at least five different levels of bias light determined by I_b:

$$s_{AM1.5G}(I_b) = \frac{\int \tilde{s}(\lambda, I_b) E_{ref}(\lambda) d\lambda}{G_{STC}} \quad \text{(A.11)}$$

with

$$G_{STC} = \int E_{ref}(\lambda) d\lambda = 1000 \frac{W}{m^2} \quad \text{(A.12)}$$

and

$$I_b = I_{sc}(E_b) \quad \text{(A.13)}$$

d) The calibration value of the short-circuit current under STC conditions I_{STC} is calculated from the following formula:

$$E_{STC} = \int_0^{I_{STC}} \frac{1}{s_{AM1.5G}(I_b)} dI_b \quad \text{(A.14)}$$

where the upper integration limit I_{STC} is obtained by iterative approximation. Refer to IEC 60904-10 for determination of whether the PV reference device can be considered linear.

A.3.5 Uncertainty estimate

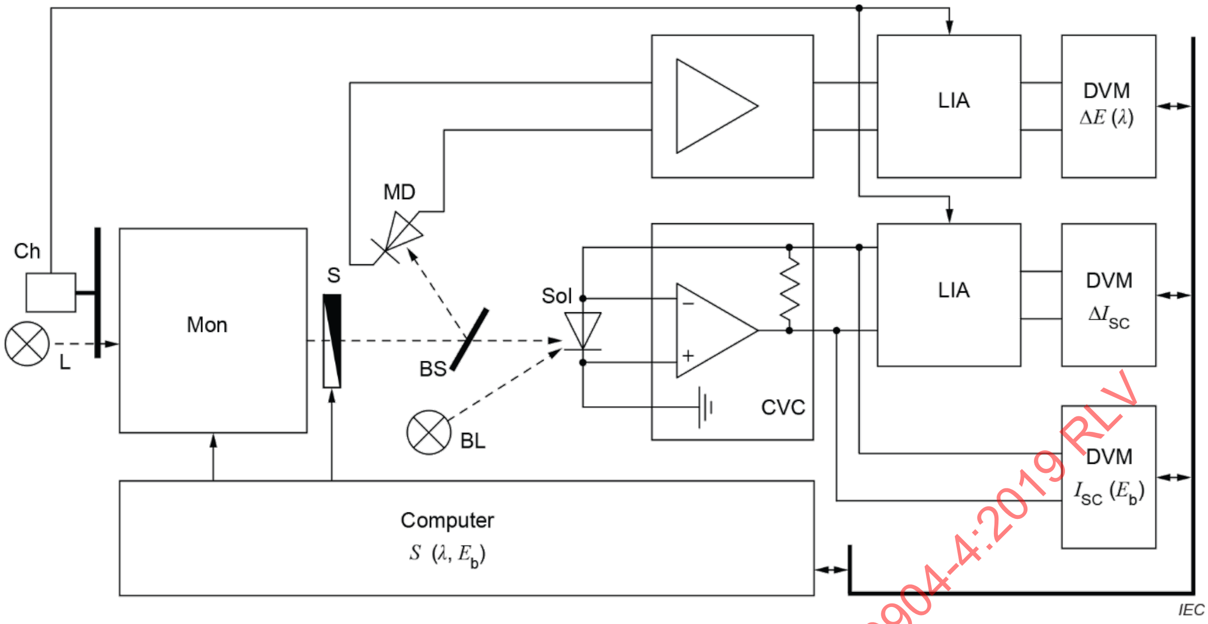
In Table A.2, typical values of the uncertainty components resulting in a combined expanded uncertainty of U_{95} < ~~1~~ 0,5 % (with coverage factor k = 2) are summarized.

NOTE ~~The dominant component in the uncertainty is that from the standard detector.~~ The uncertainty quoted is not easily achieved and might only be available at some national metrological institutes.

Table A.2 – ~~Typical~~ Uncertainty components (k = 2) of differential spectral responsivity calibration method on PV reference devices

~~Uncertainty of the standard detector(s)~~	~~< 0,5 %~~
~~Uncertainty due to nonlinear or narrow-band cells~~	~~< 0,1 %~~
~~Uncertainty due to unstable cell temperature (± 2 K)~~	~~< 0,2 %~~
~~Transfer uncertainties due to~~ ~~Relative spectral responsivity~~ ~~Absolute spectral responsivity at discrete wavelength(s)~~ ~~Spectral mismatch between bias radiation and reference solar spectrum; non-uniformity of bias radiation; non-uniformity of monochromatic radiation; mismatch of cell area and irradiated area (image of the diaphragm); spectral bandwidth (≤ 20 nm) of the monochromatic radiation; nonlinearity of the amplifiers~~	 ~~Not applicable~~ ~~< 0,1 %~~ ~~< 0,2 %~~
~~Combined expanded uncertainty~~	**~~< 1 %~~**

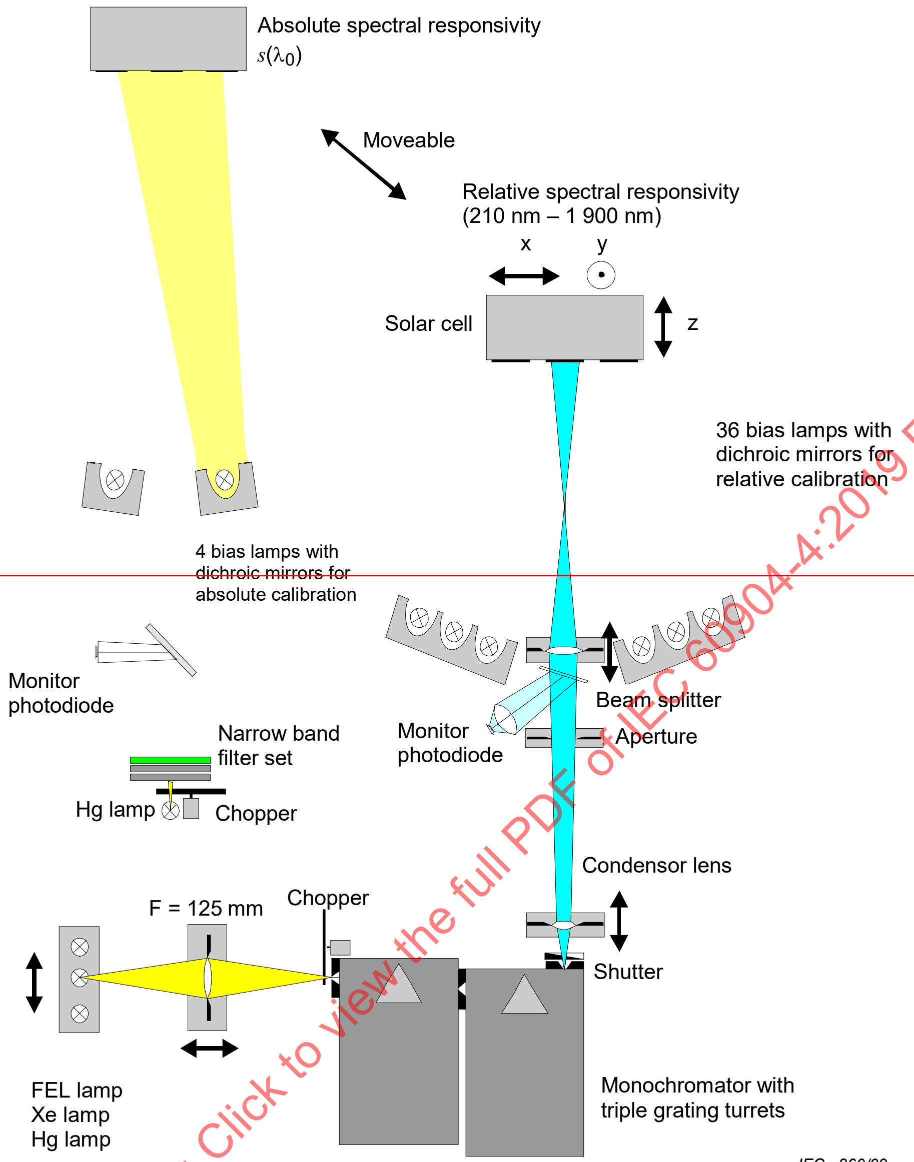
Uncertainty due to unstable device temperature (±0,5 K)	0,1 %
Uncertainty of the standard detector(s)	0,2 %
Uncertainty due to nonlinear and/or narrow-band devices	0,1 %
Transfer uncertainties (repeatability) due to relative spectral responsivity	0,1 %
Transfer uncertainties (repeatability) due to absolute spectral responsivity at discrete wavelength(s)	0,1 %
Spectral mismatch between bias radiation and reference solar spectrum; non-uniformity of bias radiation; non-uniformity of monochromatic radiation; mismatch of device area and irradiated area (image of the aperture); spectral bandwidth (< 11 nm) of the monochromatic radiation; nonlinearity of the amplifiers; determination of reference plane of standard detector and PV reference device, wavelength calibration and reproducibility of the monochromatic light source	0,4 %
Combined expanded uncertainty	0,5 %
In this table, typical values on the uncertainty components resulting in a combined expanded uncertainty of U_{95} < 0,5 %, with coverage factor k = 2, are summarized. It is not required that the PV reference device is linear, and there are no restrictions on the shape of the spectral responsivity curve of the device; however, temperature control of the device within ±1 K is recommended.	



Key

Mon	monochromator
Ch	chopper
L	light source with entrance optics
S	shutter
BS	beam splitter
MD	monitor photodiode
BL	(array of) bias lamp(s)
Sol	~~solar cell~~ PV device and standard detector respectively
CVC	current-voltage converter
LIA	lock-in amplifier
DVM	digital voltmeter

Figure A.1 – Block diagram of differential spectral responsivity calibration superimposing chopped monochromatic radiation $DE(l)$ and DC bias radiation E_b


Absolute spectral responsivity
$s(\lambda_0)$
Moveable
Relative spectral responsivity
(210 nm – 1 900 nm)
x
y
Solar cell
z
36 bias lamps with
dichroic mirrors for
relative calibration
4 bias lamps with
dichroic mirrors for
absolute calibration
Monitor
photodiode
Beam splitter
Monitor
photodiode
Aperture
Narrow band
filter set
Hg lamp
Chopper
Condensor lens
F = 125 mm
Chopper
Shutter
FEL lamp
Xe lamp
Hg lamp
Monochromator with
triple grating turrets

IEC 860/09

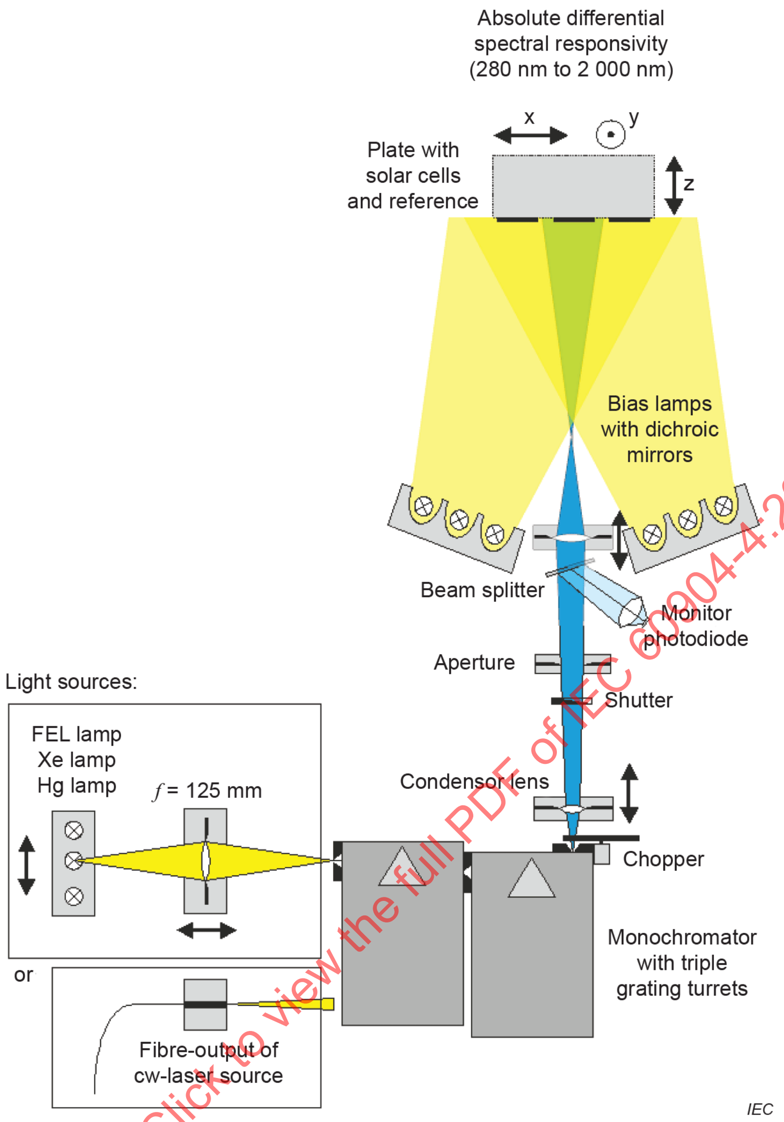


Figure A.2 – Optical arrangement of differential spectral responsivity calibration

A.3.6 Reference documents

- IEC 60904-9: *Photovoltaic devices – Part 9: Solar simulator performance requirements*
- IEC 60904-10: *Photovoltaic devices – Part 10: Methods of linearity measurements*
- J. Metzdorf, "Calibration of solar cells. 1: The differential spectral responsivity method", *Appl. Optics* **26** (9), 1987, 1701-1708
- J. Metzdorf, S. Winter, T. Wittchen, "Radiometry in photovoltaics: calibration of reference solar cells and evaluation of reference values", *metrologia* **37,** 2000, 573-578
- S. Winter, T. Wittchen, J. Metzdorf, "Primary Reference Cell Calibration at the PTB Based on an Improved DSR Facility", *Proc. 16th European Photovoltaic Solar Energy Conf.*, ed. by H. Scherr, B. Mc/Velis, E. Palz, H. A. Ossenbrink, E. Dunlop, P. Helm, Glasgow, 2000, James & James (Science Publ., London), ISBN 1 902916 19 0
- S. Winter, T. Fey, I. Kröger, D. Friedrich, K. Ladner, B. Ortel, S. Pendsa, F. Witt, "Design, realization and uncertainty analysis of a laser-based primary calibration facility for solar cells at PTB", *Measurement* **51**, 2014, 457-463.

A.4 Solar simulator method (SSM)

A.4.1 General

Traceability is based on the absolute spectral irradiance of simulated sunlight and relative spectral responsivity of the PV reference ~~solar cell~~ device to be calibrated. The absolute spectral irradiance shall be measured by a spectroradiometer calibrated by standard lamps directly traceable to SI units, and the spectral responsivity shall be calibrated by standard detectors directly traceable to SI units. When traceability via WRR is required, the absolute irradiance of the solar simulator shall be measured by using a cavity radiometer traceable to the WRR. The calibration value is computed from the measured spectral responsivity of the PV reference ~~cell~~ device, the spectral irradiance distribution of the solar simulator and the reference solar spectral irradiance distribution (IEC 60904-3).

A.4.2 Equipment

The following apparatus is required (see Figure A.3).

a) A solar simulator of class AAA as defined in IEC 60904-9. The uncertainty analysis below assumes that spatial non-uniformity of irradiance is below 0,2 % and temporal instability is below 0,1 %. When the cavity radiometer (A.4.2.e) is used the solar simulator shall be steady-state with collimated light beam.

b) A spectroradiometer as described in CIE 53-1982.

c) Means for measuring relative spectral responsivity of the PV reference ~~cell~~ device as defined in IEC 60904-8.

d) A standard lamp which has been directly calibrated by the primary standard lamps, which shall be mutually recognized and authorized by CCPR/CIE.

e) A cavity radiometer traceable to the WRR whose view angle is wider than the spreading angle of the solar simulator light (optional).

f) Means for measuring the short-circuit current of the PV reference ~~cell~~ device which shall comply with the general measurement requirements of IEC 60904-1.

g) Means for maintaining the temperature of the PV reference ~~cell~~ device at (25 ± 2)°C if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval.

A.4.3 Calibration procedure

a) The relative spectral ~~response~~ responsivity of the PV reference ~~cell~~ device shall be measured ~~with white bias light of 1 000 Wm^{-2} at (25 ± 2)°C~~ in accordance with IEC 60904-8.

b) The irradiance of the solar simulator in the test plane shall be set to approximately ~~1 000 Wm^{-2}~~ G_{STC}, using a thermal photo detector such as a thermopile.

c) The absolute spectral irradiance distribution in the test plane shall be measured by the calibrated spectroradiometer as described in CIE 63-1984. For the calculation as described in A.4.4 a) the wavelength range has to span at least the same interval as $s(\lambda)$. When the cavity radiometer is used as in A.4.4. b), the wavelength range of the spectral irradiance measurement shall be sufficiently large to reach the desired uncertainty.

~~NOTE For the calculation as described in A.4.3 a) the wavelength range has to span at least the same interval as S(λ). When the cavity is used as in A.4.3. b), the wavelength range of the spectral irradiance measurement must be sufficiently large to reach the desired uncertainty.~~

d) The PV reference ~~cell~~ device shall be located in the test plane of the simulator. The ~~cell~~ device temperature shall be maintained at (25 ± 2)°C throughout all calibration runs if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval. The short-circuit current of the ~~cell~~ device is to be measured more than 10 times and the mean value is to be calculated.

A.4.4 Data analysis

a) The calibration value (CV) is to be computed as follows.

$$\cancel{CV = I_{SC} \frac{\int E_s(\lambda)S(\lambda)\,d\lambda}{\int E_m(\lambda)S(\lambda)\,d\lambda}}$$

$$CV = I_{SC} \frac{\int_0^{\infty} E_{ref}(\lambda)s(\lambda)d\lambda}{\int_0^{\infty} E_{meas}(\lambda)s(\lambda)d\lambda} \quad \text{(A.15)}$$

where:

~~E_m~~ $E_{meas}(\lambda)$ is the absolute spectral irradiance distribution of the solar simulator.

b) When direct traceability to WRR is required, the absolute irradiance of the solar simulator shall be measured by using a cavity radiometer traceable to the WRR, as described in A.4.2.e). The calibration value (CV) is computed according to Formula (A.4). G_T is the total irradiance of the solar simulator measured by the cavity radiometer ~~traceable to WRR~~.

c) Repeating the steps in A.4.3. and A.4.4 twice, the mean CV is to be calculated as the final calibration value.

A.4.5 Uncertainty estimate

In the following Tables A.3 and A.4, typical values of the uncertainty components resulting in combined expanded uncertainty of U_{95} of 2 % and 0,6 % (with coverage factor k = 2) are summarized.

Table A.3 – Example of uncertainty components (k = 2) of a solar simulator method calibration

Uncertainty of the standard lamp:	< 2 %
Uncertainty due to spectroradiometer:	< 0,2 %
Uncertainty due to unstable ~~cell~~ device temperature:	< 0,2 %
Transfer uncertainties due to spectral responsivity, spectral mismatch between solar simulator and reference solar spectrum:	< 0,2 %
Uncertainty due to temporal and spatial non-uniformity of solar simulator and different size and time constant of spectroradiometer and ~~cell~~ device:	< 0,2 %
Combined expanded uncertainty	2 %

Table A.4 – Typical uncertainty components (k = 2) of a solar simulator method calibration when WRR traceable cavity radiometer is used

Uncertainty of WRR versus SI units	~~< 0,4~~ 0,18 %
Uncertainty of irradiance measurement	< 0,2 %
Uncertainty due to unstable ~~cell~~ device temperature:	< 0,2 %
Uncertainties due to spectral irradiance deviations between test conditions and the reference spectral irradiance of AM1.5G (IEC 60904-3) or spectral mismatch correction (IEC 60904-7)	< 0,3 %
Uncertainty due to temporal and spatial non-uniformity of solar simulator and different size and time constant of spectroradiometer, ~~cell~~ device and cavity radiometer:	< 0,2 %
Combined expanded uncertainty	0,6 %

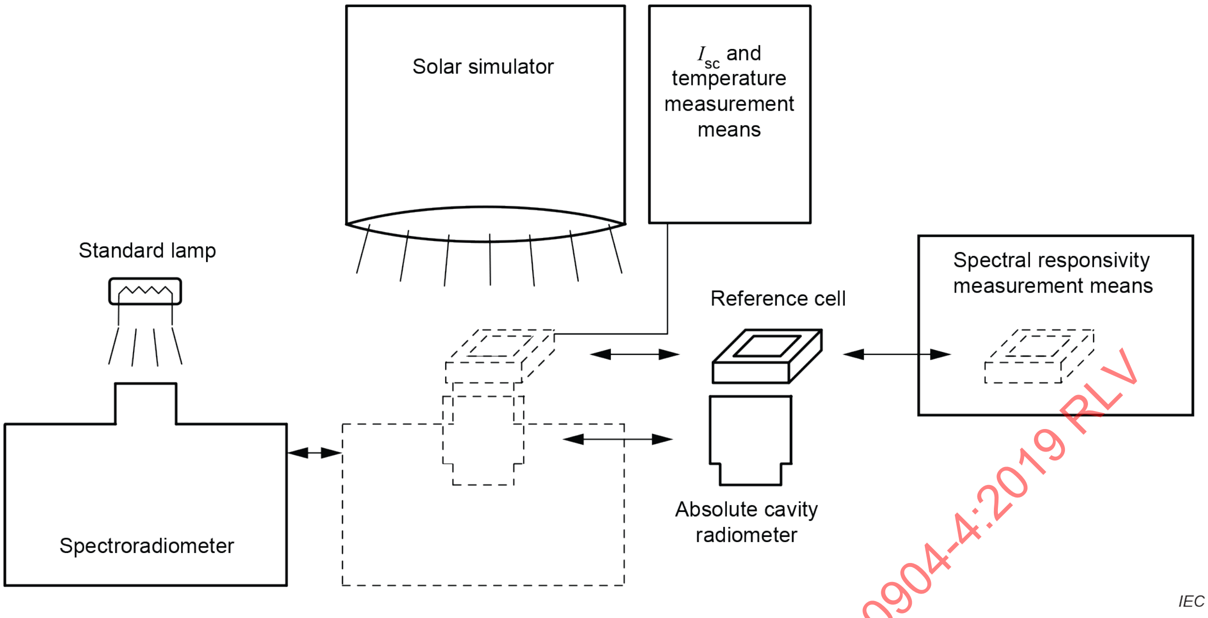


Figure A.3 – Schematic apparatus of the solar simulator method

A.4.6 Reference documents

– IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

– IEC 60904-8: *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

– IEC 60904-9: *Photovoltaic devices – Part 9: Solar simulator performance requirements*

– R. Shimokawa, F. Nagamine, Y. Miyake, K. Fujisawa, Y. Hamakawa, “Japanese indoor calibration method for the reference solar cell and comparison with outdoor calibration”, *Japanese J. Appl. Phys.* **26**(1), 1987, 86-91

– R. Shimokawa, H. Ikeda, Y. Miyake, S. Igari, "Development of wide field-of-view cavity radiometer for solar simulator use and intercomparison between irradiance measurements based on the world radiometer reference and electrotechnical laboratory scales", *Japanese J. Appl. Phys.* **41,** 2002, 5088-5093

– H. Müllejans, W. Zaaiman, F. Merli, E. D. Dunlop, H. A. Ossenbrink, “Comparison of traceable calibration methods for primary photovoltaic reference cells”, *Progress in Photovoltaics* **13,** 2005, 661-671

– CIE 53-1982, *Methods of Characterizing the Performance of radiometers and Photometers*, ISBN 92 9034 053 3

– CIE 63-1984, *The Spectroradiometric Measurement of Light Sources*

A.5 Direct sunlight method (DSM)

A.5.1 General

The PV reference ~~solar cell~~ device to be calibrated is compared under direct-beam natural sunlight with a reference radiometer. The establishment of traceability is based on the calibration using a pyrheliometer measuring direct solar irradiance and traceable to the WRR. The short-circuit current of the ~~solar cell~~ PV reference device is measured, scaled to ~~1 000 W/m²~~ G_{STC} and corrected for temperature and spectral mismatch between the direct-beam natural sunlight spectrum as measured by a spectroradiometer and the defined standard spectrum (IEC 60904-3). The relative spectral ~~response~~ responsivity of the ~~solar cell~~ PV reference device also has to be determined according to IEC 60904-8.

A.5.2 Equipment

a) A mounting platform, which can be oriented normal to the sun within an accuracy of ±0,5° throughout the calibration run.

b) A cavity radiometer, traceable to the WRR.

c) A collimator tube for the ~~solar cell~~ PV reference device having the same viewing angle as the cavity radiometer.

d) A temperature-controlled mounting block for the PV reference ~~cell~~ device to be calibrated capable of maintaining the junction temperature at (25 ± 2) °C throughout all calibration runs if temperature corrections are not applied. ~~Means to measure the temperature of the reference solar cell to be calibrated.~~ The uncertainty analysis assumes that temperature corrections are applied and the temperature is stable within 0,2 °C during the data collection interval.

e) Traceable means to measure the short-circuit current of the ~~solar cell~~ PV reference device to an accuracy of ±0,1 % or better.

f) A spectroradiometer for measuring the direct normal solar spectral irradiance with the same viewing angle as the cavity radiometer.

g) An apparatus to measure the relative spectral ~~response~~ responsivity of the ~~solar cell~~ PV reference device according to IEC 60904-8 and as a function of temperature.

A.5.3 Measurements

A calibration according to this document shall be performed only on clear, sunny days with no visible cloud cover within 30° of the sun.

a) Mount the PV reference ~~cell~~ device to be calibrated with the collimator, the cavity radiometer, and the spectroradiometer coplanar on the tracking platform.

b) Measure the relative spectral irradiance of the sun, ~~E_m~~ $E_{meas}(\lambda)$, using the spectroradiometer. During the spectral irradiance measurement, perform the following steps simultaneously:

   1) Measure the cavity radiometer output, G_{dir}, and verify that the ~~total~~ irradiance is between 750 Wm^{-2} and 1 100 Wm^{-2}.

   2) Measure the short-circuit current I_{SC} of the PV reference ~~solar cell~~ device to be calibrated.

   3) Measure the PV reference ~~cell~~ device temperature, T_j.

   4) Repeat these steps at least four times. These repetitions shall be distributed in time during ~~the~~ a single spectral irradiance measurement.

c) Perform a minimum of five replications of step b) on at least three separate days.

A.5.4 Data analysis

a) Perform the correction of Formula (A.1), where G_T is the reading of the cavity radiometer representing the direct irradiance G_{dir}.

b) Average the calibration values from a) for each measurement of spectral irradiance.

~~c) Extend the measured spectral irradiance to the range 300-4 000 nm according to reference documents to encompass the limits of the standard spectrum (IEC 60904-3).~~

~~d) Correct each result of step b) for temperature using Equation A.2 and then for spectral effects according to Equation A.3 where $E_m(\lambda)$ is the direct beam solar spectral irradiance, giving the CV according to Equation A.4.~~

c) Correct the data to 25 °C and translate the data to the reference spectrum.

   Correct each result of step b) for temperature and spectral effect according to Formula (A.16) giving one CV_i according to Formula (A.17).

$$F\left(T_\mathrm{j}\right)=\frac{\int_0^\infty E_\mathrm{ref}\left(\lambda\right)d\lambda}{\int_0^\infty E_\mathrm{meas}\left(\lambda\right)d\lambda}\frac{\int_0^\infty E_\mathrm{meas}\left(\lambda\right)\left[s\left(\lambda,25\ ^\circ\mathrm{C}\right)+\left(T_\mathrm{j}-25\ ^\circ\mathrm{C}\right)\frac{\partial s\left(\lambda,T_\mathrm{j}\right)}{\partial T}\right]d\lambda}{\int_0^\infty E_\mathrm{ref}\left(\lambda\right)s\left(\lambda,25\ ^\circ\mathrm{C}\right)d\lambda} \quad \text{(A.16)}$$

$$CV_i=I_\mathrm{SC}\frac{M_\mathrm{G}}{F\left(T_\mathrm{j}\right)} \quad \text{(A.17)}$$

d) Average ~~the calibration values~~ all CV_i for each day and calculate the arithmetic average CV using Formula (A.5).

e) Reject any points that meet the following criteria:

1) CV_i more than 1,5 % from CV;
2) I_SC range is greater than 1,5 %;
3) $CV_i\ (T_\mathrm{j})$ standard deviation is > 1 %.

f) Verify that at least three days data with a minimum of five sets per day of valid data exist. If not take additional measurements until this criterion is met. Typically five days of data with 10 sets per day of valid data are used obtained to further reduce the standard deviation of CV.

A.5.5 Uncertainty estimate

In Table A.5, typical values of the uncertainty components for the direct sunlight method are listed, resulting in combined expanded uncertainty U_{95} (with coverage factor k = 2) of ~~0,9~~ 0,6 %.

Table A.5 – Typical uncertainty components (k = 2) of a direct sunlight method using temperature dependent spectral correction factor (Formula (A.16)), without applying a correction factor for the WRR to SI scale

~~Uncertainty of WRR vs SI units~~	~~0,4 %~~
~~Measured direct irradiance~~	~~0,2 %~~
~~Spectral mismatch correction~~	~~0,8 %~~
~~Uncertainty due to cell temperature correction~~	~~0,2 %~~
~~Combined expanded uncertainty~~	~~0,9 %~~

Uncertainty of scale difference WRR versus SI	0,34 %
Measured direct irradiance	< 0,18 %
Spectral mismatch correction	0,05 %
Uncertainty due to device temperature correction	< 0,1 %
Combined expanded uncertainty	0,46 %

A.5.6 Reference documents

– IEC 60904-8: *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

– C.R. Osterwald, K.A. Emery, D.R. Myers, R.E. Hart, “Primary reference cell calibrations at SERI: History and methods”, *Proc. 21st IEEE PVSC* Orlando, FL, May 21-25 1990, 1062-1067

– K.A. Emery, C.R. Osterwald, L.L. Kazmerski, R.E. Hart, “Calibration of primary terrestrial reference cells when compared with primary AM0 reference cells", *Proc. 8th European PVSEC*, Florence, Italy, May 9-12 1988 p. 64-68

– C. Osterwald, K. Emery, "Spectroradiometric Sun Photometry" *Journal of Atmospheric and Oceanic Technology*, **17,** 2000, 1171-1188

– ASTM E 1125-10: *Standard test method for calibration of primary non-concentrator terrestrial photovoltaic reference cells using a tabular spectrum*

– ASTM E 1125-16: *Standard test method for calibration of primary non-concentrator terrestrial photovoltaic reference cells using a tabular spectrum*

– A Fehlmann, G Kopp, W Schmutz, R Winkler, W Finsterle, N Fox, *metrologia* **49,** 2012, S34

– C.R. Osterwald, M. Campanelli, T. Moriarty, K.A. Emery, R. Williams "Temperature-Dependent Spectral Mismatch Corrections," *IEEE Journal of Photovoltaics* **5**, 2015, 1692-1697

– C.R. Osterwald, L. Ottoson, R. Williams, C. Mack, T. Moriarty, K.A. Emery, and D.H. Levi, "Primary Reference Cell Calibrations with Reduced Measurement Uncertainty," *Proc. 44th IEEE Photovoltaic Spec. Conf.*, Washington, DC, June, 2017

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~~IEC 60891, *Procedures for temperature and irradiance corrections to measure I-V characteristics of crystalline silicon photovoltaic devices*~~

~~IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*~~

~~IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*~~

~~IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*~~

~~IEC 60904-8, *Photovoltaic devices – Part 8: Measurement of spectral response of a photovoltaic (PV) device*~~

~~IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*~~

~~IEC 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*~~

~~ISO/IEC Guide 99:2007, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*~~

~~NIST Technical Note 1297:1994, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurements Results*~~

~~*The Expression of Uncertainty and Confidence in Measurement*, United Kingdom, Accreditation Service, M3003, Middlesex, UK, December 1997~~

ISO 9846, *Solar energy – Calibration of a pyranometer using a pyrheliometer*

ISO 9847, *Solar energy – Calibration of field pyranometers by comparison to a reference pyranometer*

ISO 9059, *Solar energy – Calibration of field pyrheliometers by comparison to a reference pyrheliometer*

IEC 60904-4

Edition 2.0 2019-11

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Photovoltaic devices –
Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability

Dispositifs photovoltaïques –
Partie 4: Dispositifs photovoltaïques de référence – Procédures pour établir la traçabilité de l'étalonnage

IEC 60904-4:2019-11(en-fr)

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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PHOTOVOLTAIC DEVICES –

Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability

FOREWORD

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International Standard IEC 60904-4 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This second edition cancels and replaces the first edition published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) modification of standard title;
b) inclusion of working reference in traceability chain;
c) update of WRR with respect to SI;
d) revision of all methods and their uncertainties in Annex A;
e) harmonization of symbols and formulae with other IEC standards.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
82/1618/FDIS	82/1638/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60904 series, published under the general title *Photovoltaic devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

The contents of the corrigendum of September 2020 have been included in this copy.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

PHOTOVOLTAIC DEVICES –

Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability

1 Scope

This part of IEC 60904 sets the requirements for calibration procedures intended to establish the traceability of photovoltaic (PV) reference devices to SI units as required by IEC 60904-2.

This document applies to PV reference devices that are used to measure the irradiance of natural or simulated sunlight for the purpose of quantifying the performance of PV devices. The use of a PV reference device is required in many standards concerning PV (e.g. IEC 60904-1 and IEC 60904-3).

This document has been written with single-junction PV reference devices in mind, in particular crystalline silicon, but it is sufficiently general to include other single-junction technologies.

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.

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-2, *Photovoltaic devices – Part 2: Requirements for photovoltaic reference devices*

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

ISO/IEC Guide 98-3: 2008, *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 terms and definitions given in IEC TS 61836 and the following apply.

NOTE The different reference instruments for the traceability chain of solar irradiance are defined in this clause. Typical examples for each category are listed in Table 1, which also refers to relevant standards (where available). Figure 1 then shows schematically the most common traceability chains linking these instruments and the relevant standards (where available). Methods for the implementation of this document are described in Annex A.

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

- IEC Electropedia: available at http://www.electropedia.org/

- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
primary standard
standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity

Note 1 to entry: The concept of a primary standard is equally valid for base quantities and derived quantities.

Note 2 to entry: A primary standard is never used directly for measurement other than for comparison with other primary standards or secondary standards.

Note 3 to entry: Primary standards are usually maintained by national metrology institutes (NMIs) or similar organizations entrusted with maintenance of standards for physical quantities. Often referred to also just as the «primary», the physical implementation is selected such that long-term stability, accuracy and repeatability of measurement of the quantity it represents are guaranteed to the maximum extent possible by current technology.

Note 4 to entry: The World Radiometric Reference (WRR) as realized by the World Standard Group (WSG) of cavity radiometers is the accepted primary standard for the measurement of solar irradiance.

3.2
secondary standard
device which, by periodical comparison with a primary standard, serves to maintain conformity to SI units at other places than that of the primary standard

Note 1 to entry: A secondary standard does not necessarily use the same technical principles as the primary standard, but strives to achieve similar long-term stability, accuracy and repeatability.

Note 2 to entry: Typical secondary standards for solar irradiance are cavity radiometers which participate periodically (normally every 5 years) in the International Pyrheliometer Comparison (IPC) with the WSG, thereby giving traceability to WRR. Direct traceability to SI radiometric scale can also be available for these instruments.

3.3
primary reference
instrument which a laboratory uses to calibrate secondary references, compared at periodic intervals to a secondary standard

Note 1 to entry: Often primary references can be realized at much lower costs than secondary standards.

Note 2 to entry: Typically, a PV cell is used as a reference device for the measurement of natural or simulated solar irradiance. Primary references are normally used by calibration and testing laboratories.

3.4
secondary reference
measurement device in use for daily routine measurements or to calibrate working references, calibrated at periodic intervals against a primary reference

Note 1 to entry: The most common secondary references for the measurement of natural or simulated solar irradiance are PV cells and PV modules. Secondary references are normally used by calibration and testing laboratories, but sometimes also in industrial production.

3.5
working reference
measurement device in use for daily routine measurements, calibrated at periodic intervals against a secondary reference

Note 1 to entry: The most common working references for the measurement of natural or simulated solar irradiance are PV cells and PV modules.

Note 2 to entry: Working references are normally used in industrial production.

3.6
traceability
<of a PV reference device> requirement for any PV reference device, to tie its calibration value to SI units in an unbroken and documented chain of calibration transfers including stated uncertainties

Note 1 to entry: The WRR has been compared several times to the SI radiometric scale. While in previous comparisons the two scales were found to be indistinguishable within the uncertainty of the comparison, the latest comparison of scales established that there is a systematic shift between the scales, with WRR reading 0,34 % higher irradiance than the SI scale. The uncertainty of this shift was given as 0,18 % (k = 2). Therefore, traceability to WRR automatically provides traceability to SI units. However, the shift between the scales may be corrected for those measurements traceable to the WRR. The uncertainty of the scale comparison shall be included into the uncertainty budget. Essentially there are two possibilities for those measurements traceable to SI units via the WRR. Firstly, no correction is applied for the scale difference and a larger uncertainty of 0,3 % (rectangular distribution) shall be used. Secondly an explicit correction of the scale difference amounting to 0,34 %. In this case the uncertainty contribution is 0,18 % (k = 2). The value of 0,34 % for the scale difference is the latest available at time of publication of this document. The scientific literature should be checked for possible updates of this difference and its uncertainty. In particular, it is possible that in the future the WRR is adapted to take account of this difference and bring it into line with SI units. In this case no further correction shall be applied.

[SOURCE: A Fehlmann, G Kopp, W Schmutz, R Winkler, W Finsterle, N Fox, *metrologia* **49** (2012) S34]

Table 1 – Examples of reference instruments used in a traceability chain of solar irradiance

Reference instrument	Solar irradiance
Primary standard	Group of cavity radiometers constituting the World Standard Group (WSG) of the World Radiometric Reference (WRR) Cryogenic trap detector Standard lamp
Secondary standard	Commercially available cavity radiometers compared regularly (normally every 5 years) at the International Pyrheliometer Comparison (IPC) Standard detector calibrated against a trap detector Spectroradiometer calibrated against a standard lamp
Primary reference	Normal incidence pyrheliometer (NIP) (ISO 9059) PV reference device (IEC 60904-2 and IEC 60904-4)
Secondary reference	Pyranometer (ISO 9846) PV reference device (IEC 60904-2)
Working reference	Pyranometer (ISO 9847) PV reference device (IEC 60904-2)

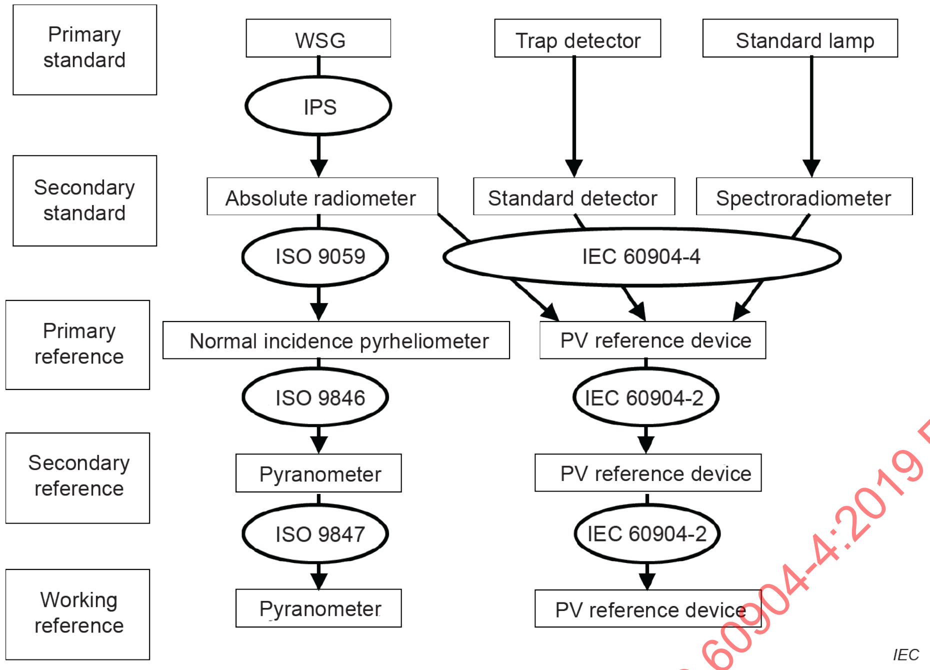

Figure 1 – Schematic of most common reference instruments and transfer methods used in the traceability chains for solar irradiance detectors

4 Requirements for traceable calibration procedures of PV reference devices

A traceable calibration procedure is necessary to transfer calibration from a standard or reference measuring solar irradiance and based on a physical principle other than PV effect (such as cavity radiometer, pyrheliometer and pyranometer) to a PV reference device. The requirements for such procedures are as follows:

a) Any measurement instrument required and used in the transfer procedure shall be an instrument with an unbroken traceability chain.
b) A documented uncertainty analysis.
c) Documented repeatability, such as measurement results of laboratory intercomparison, or documents of laboratory quality control.
d) Inherent absolute accuracy, given by a limited number of intermediate transfers.

Normally the transfer would be from a secondary standard to a PV reference device constituting a primary reference.

The transfer from one PV reference device to another is covered by IEC 60904-2.

5 Uncertainty analysis

An uncertainty estimate according to ISO/IEC Guide 98-3: 2008 shall be provided for each traceable calibration procedure. This estimate shall provide information on the uncertainty of the calibration procedure and quantitative data on the following uncertainty factors for each instrument used in performing the calibration procedure. In particular:

a) Component of uncertainty arising from random effects (Type A).
b) Component of uncertainty arising from systematic effects (Type B).

A full uncertainty analysis has to be performed for the implementation of the calibration method by a particular laboratory. Annex A provides examples of the main uncertainty components in some particular implementations. Due to the variety of methods available, it is impossible to give a detailed guidance on how a particular uncertainty analysis should be made. However, the following components shall be considered:

– uncertainty of all measurement instruments involved;
– offset and drift of all measurement instruments;
– uncertainty of all references used;
– uncertainty of measured device temperature;
– uncertainty introduced of deviations between actual and nominal device temperature;
– uncertainty of irradiance measurement (total and spectral irradiance);
– uncertainty introduced by deviations between actual and reference spectral irradiance;
– contributions due to repeatability and reproducibility;
– uncertainty due to instability of conditions and instruments.

6 Calibration report

The calibration report shall include at least the following information:

a) title (e.g. "Calibration Certificate");
b) name and address of laboratory, and location where the calibrations were carried out, if different from the address of the laboratory;
c) unique identification of the report (such as serial number) and of each page, the total number of pages and the date of issue;
d) name and address of the client placing the order;
e) description and unambiguous identification of the item(s) calibrated;
f) date of receipt of calibration item(s) and date(s) of performance of calibration, as appropriate;
g) calibration results and their uncertainties, including the temperature of the device at which the calibration was performed;
h) reference to sampling procedures used by the laboratory where these are relevant to the validity or application of the results;
i) the name(s), title(s) and signature(s) or equivalent identification of person(s) authorizing the report;
j) where relevant, a statement to the effect that the results relate only to the items calibrated;
k) where relevant the spectral responsivity of the PV reference device;
l) where relevant the temperature coefficient of the PV reference device.

7 Marking

The calibrated PV reference device shall be marked with a serial number or reference number and the following information attached or provided on an accompanying certificate:

a) date of (actual or present) calibration;
b) calibration value and its uncertainty;
c) identification of laboratory having performed the calibration.

Annex A
(informative)

Examples of validated calibration procedures

A.1 General

A.1.1 Overview

Annex A describes examples of calibration procedures for PV reference devices as primary reference devices, together with their stated uncertainties. These procedures serve to establish the traceability of PV reference devices to SI units as required by IEC 60904-2. Primary reference devices calibrated in accordance with these procedures serve to establish the traceability of further PV reference devices, which then constitute secondary reference devices.

As already mentioned in Clause 1, the methods in this annex are limited to PV single junction technology. Moreover, they have currently only been validated for crystalline silicon technology, although they could be applicable to other technologies.

The methods have been implemented in various laboratories around the world and validated in international intercomparisons, most notably the World Photovoltaic Scale (WPVS). However, the description in this document is more generalized. For details of the various implementations, the references in peer-reviewed publications are given at the end of each procedure.

The uncertainty estimates are based on U_{95} (coverage factor k = 2) for all single components. The combined expanded uncertainty is calculated as the square root of the sum of squares of all components. The uncertainties provided are simplified versions (restricted to the main components) as provided by the laboratories having implemented the procedure. These uncertainty calculations only serve as guidelines and will have to be adapted to the particular implementation of each procedure in a given laboratory. The uncertainties achieved by any implementation of these methods might be considerably different. Uncertainties quoted by a given laboratory have to be based on an explicit specific analysis and cannot be taken by reference to the uncertainty estimates in this document.

A.1.2 Examples of validated methods

A.2 Global sunlight method (GSM)

A.3 Differential spectral responsivity calibration (DSR)

A.4 Solar simulator method (SSM)

A.5 Direct sunlight method (DSM)

A.1.3 List of common symbols

I_{SC}	short-circuit current of PV reference device
T_j	temperature of PV reference device
M_G	irradiance correction factor (see below)
M_T	temperature correction factor (see below)
T_{coef}	temperature coefficient α of the short-circuit current (IEC 60891) normalized to the short-circuit current at 25 °C and expressed in 1/ K
SMM	spectral mismatch factor (IEC 60904-7)
λ	wavelength
$s(\lambda)$	spectral responsivity of PV reference device as a function of wavelength λ

$s(\lambda,T_j)$	spectral responsivity of PV reference device as a function of wavelength λ and temperature T_j
$\frac{\partial s(\lambda,T_j)}{\partial T}$	partial derivative of spectral responsivity with respect to temperature as a function of wavelength λ
$\tilde{s}(\lambda)$	differential spectral responsivity of PV reference device
$E_{meas}(\lambda)$	spectral irradiance distribution of natural or simulated sunlight
$E_{ref}(\lambda)$	standard or reference spectral irradiance distribution according to IEC 60904-3
G_{dir}	direct irradiance
G_{dif}	diffuse in-plane irradiance
G_T	total in-plane irradiance
G_{STC}	irradiance at STC (= 1 000 Wm–2)
CV	calibration value, i.e. I_{SC} at STC
AM	air mass
STC	standard test conditions (1 000 Wm^{-2}, 25 °C and $E_{ref}(\lambda)$)
P	local air pressure
P_0	101 300 Pa
θ	solar elevation angle

A.1.4 Common formulae

The methods described in Clauses A.2, A.4 and A.5 have some common calculations, which are detailed in A.1.4. Details of the various implementations are then described in each subclause.

The I_{SC} is normally not measured at exactly 1 000 Wm^{-2}, but at an irradiance level close to it. Under the assumption that the I_{SC} of the PV reference device varies linearly with irradiance according to IEC 60904-10, the following correction is made:

$$I_{SC}(G_{STC}) = I_{SC} M_G = I_{SC} \frac{G_{STC}}{G_T} \tag{A.1}$$

If the irradiance measurement is traceable to the WRR, then the irradiance reading may be corrected for the scale difference to SI units.

STC mandate a device temperature of 25 °C, but measurements will not always be taken at this temperature. The deviations in temperature should be accounted for in the uncertainty budget. It is also possible to correct I_{SC} from the measurement temperature T_j to 25 °C by multiplying with the temperature correction factor M_T defined by:

$$I_{SC}(25\ ^\circ\mathrm{C}) = I_{SC}(T_j) M_T = \frac{I_{SC}(T_j)}{1 - T_{coef}(25\ ^\circ\mathrm{C} - T_j)} \tag{A.2}$$

The correction for the difference in spectral responsivity of the PV reference device to be calibrated and the device used to measure the irradiance can be calculated as a spectral mismatch *SMM:*

$$SMM = \frac{\int_0^\infty E_{\mathrm{ref}}(\lambda)\,d\lambda}{\int_0^\infty E_{\mathrm{meas}}(\lambda)\,d\lambda} \frac{\int_0^\infty E_{\mathrm{meas}}(\lambda)s(\lambda)\,d\lambda}{\int_0^\infty E_{\mathrm{ref}}(\lambda)s(\lambda)\,d\lambda} \tag{A.3}$$

NOTE Formula A.3 is the same formula as in IEC 60904-7 for the case of a thermopile detector where the spectral responsivity of the device under test is now the spectral responsivity of the PV reference device to be calibrated.

The integration range is over all wavelengths. For $E_{\mathrm{ref}}(\lambda)$ the irradiance is zero below 280 nm. This also holds normally for $E_{\mathrm{meas}}(\lambda)$ in particular under natural sunlight. For practical reasons the explicit integral cannot be calculated above 4 000 nm, as $E_{\mathrm{ref}}(\lambda)$ is not defined explicitly but only the integral irradiance between 4 000 nm and infinity. $E_{\mathrm{meas}}(\lambda)$ is typically only measured for an even smaller wavelength range, for example up to 2 500 nm. In order to calculate the integrals, suitable approximation (truncation of the integrals) or extension of measured spectral irradiance data by extrapolation or modelling can be used, but has to be accounted for in the uncertainty calculation. For example, the truncation of the integrals at 4 000 nm for the DSM will lead to an error of 0,025 %, whereas truncation at 2 500 nm to an error of 0,116 %. These values have been determined from the direct and global spectral irradiance as defined in IEC 60904-3.

Cavity radiometers used for irradiance measurement are assumed to detect irradiance at all wavelengths perfectly. Possible deviations from such a perfect characteristic should be corrected or accounted for in the measurement uncertainty.

The calibration value (CV) of the PV reference device is then calculated as:

$$CV = I_{\mathrm{SC}} \frac{M_{\mathrm{G}} M_{\mathrm{T}}}{SMM} \tag{A.4}$$

A.1.5 Reference documents

– IEC 60891: *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*

– IEC 60904-7: *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

– IEC 60904-10: *Photovoltaic devices – Part 10: Methods of linearity measurements*

– C. R. Osterwald et al., “The results of the PEP'93 intercomparison of reference cell calibrations and newer technology performance measurements: Final Report”, *NREL/TP-520-23477,* 1998, 209 pages

– C. R. Osterwald et al., “The world photovoltaic scale: an international reference cell calibration program”, *Progress in Photovoltaics,* **7,** 1999, 287-297

– K. Emery, “The results of the First World Photovoltaic Scale Recalibration”, *NREL/TP-520-27942,* 2000, 14 pages

– Winter el al., “The results of the Second World Photovoltaic Scale Recalibration”, *Proc. of the 31st IEEE PVSC* , 3-7 January 2005, Orlando, Florida, USA, pp. 1011-1014

A.2 Global sunlight method (GSM)

A.2.1 General

The establishment of traceability is based on the calibration using the continuous sun-and-shade method as described in ISO 9846. The PV reference device to be calibrated is compared under natural sunlight with two reference radiometers, namely a pyrheliometer measuring direct solar irradiance and a pyranometer measuring diffuse solar irradiance by application of a continuous shading device under normal incidence conditions. The total solar irradiance is determined by the sum of direct irradiance and diffuse in-plane irradiance. As a pyrheliometer, a secondary standard is used in the form of an absolute cavity radiometer regularly compared with the World Standard Group (WSG) establishing the World Radiometric Reference (WRR). The calibration factor for the PV reference device is determined from the measured short-circuit current, corrected according to Formula (A.4) based on the measured spectral irradiance of the global sunlight and the relative spectral responsivity of the PV reference device to be calibrated.

Under certain conditions the simplified global sunlight method is applicable. The short-circuit current of the PV reference device is corrected by Formulae (A.1) and (A.2) and then plotted versus pressure corrected geometric air mass (AM). The calibration value is determined from a linear least square fit at AM = 1,5. A correction according to Formula (A.3) is not required and hence the measurements of the spectral irradiance of the natural sunlight and the spectral responsivity of the PV reference device are not necessary. In the simplified version of the global sunlight method the explicit correction according to Formula (A.3) is replaced by conditions which should ensure that the spectral irradiance of the natural sunlight is sufficiently close to the defined standard spectral irradiance (IEC 60904-3) that the uncertainty component is smaller than quoted in Table A.1. Although this should be ensured by the conditions listed in the description of the method below, it should be explicitly verified (preferentially by using the full global sunlight method). After this validation the simplified version can be applied as long as the boundary conditions are the same as during the validation.

The verification and validation will produce numerical values for both methods. If the agreement between these numerical values is within the uncertainty budget of the methods, the simplified method shall be deemed validated. The simplified procedure gives accurate results for devices with a spectral responsivity over a broad range of the solar spectrum for example crystalline silicon devices, but significant errors may be introduced for narrow spectral responsivity devices.

A.2.2 Equipment

a) A mounting platform, which can be oriented normal to the sun within an accuracy of ±0,5° throughout the calibration run.

b) A cavity radiometer, traceable to the WRR.

c) A pyranometer, traceable to the WRR.

d) A shading device to provide shade to item c). The field angle, viewing angle and aperture angle provided by the shade shall compensate the respective descriptive angles of the cavity radiometer of item b).

e) A temperature controlled mounting block for the PV reference device under test capable of maintaining the device temperature at (25 ± 2) °C throughout all calibration runs if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval.

f) Traceable means to measure the short-circuit current of the PV reference device to an accuracy of ±0,1 % or better.

g) Traceable means to measure the signal of the pyranometer to an accuracy of ±0,5 % or better.

h) Not required in simplified version: A spectroradiometer capable of measuring the spectral irradiance of the total in-plane natural sunlight.

i) Not required in simplified version: Apparatus to determine the relative spectral responsivity of the PV reference device according to IEC 60904-8.

j) Only required in simplified version: Means to measure the sun’s elevation to an accuracy of ±2°. Alternatively, the elevation of the sun during the data sampling can be taken from almanacs or computed, as long as the accuracy requirement is met for the instant of data sampling. The latter normally requires traceable means to measure time for the computation of air mass.

k) Only required in simplified version: A manometer to measure the local air pressure P to an accuracy of ±250 Pa or better.

A.2.3 Measurements

A calibration according to this document shall be performed only on clear, sunny days with no visible cloud cover within 30° of the sun.

a) Not required in simplified version: Determine the relative spectral responsivity of the PV reference device to be calibrated according to IEC 60904-8.

b) Select the site and/or the season of the year to ensure that the sun's elevation reaches an angle during the course of the day which corresponds to $AM = 1{,}5$ (41,8° at P_0).

c) Mount the cavity radiometer on the sun-pointing device (item A.2.2.a). Commercially available radiometers have their own electronic unit which shall be connected to the instrument following the manufacturer's recommendations. Allow sufficient time to stabilize the electronic unit.

d) Mount the PV reference device to be calibrated coplanar on the mounting platform, attaching it to the mounting block and maintain the device temperature at (25 ± 2) °C throughout all calibration runs if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval.

e) Mount the pyranometer intended to measure diffuse solar irradiance coplanar on the mounting platform. Ensure that within the field of view of the pyranometer no reflective surfaces influence the measurement result. Mount the shading device and ensure that the sensitive area of the pyranometer is pointed to the centre of the shade.

f) Not required in simplified version: Mount the spectroradiometer coplanar on the mounting platform.

g) Take simultaneous readings according to the following steps:

   1) Ensure the alignment of all instruments with respect to the sun and the proper alignment of the shading device.

   2) Ensure that the temperature of the PV reference device is within the limits given in d).

   3) Record G_{dir}, the direct normal irradiance as indicated by the cavity radiometer.

   4) Record G_{dif}, the diffuse in-plane irradiance as indicated by the pyranometer.

   5) Record I_{SC}, the short-circuit current of the PV reference device to be calibrated.

   6) Not required in simplified version: Record $E_{\text{meas}}(\lambda)$, the spectral irradiance of the global natural sunlight.

   7) Only required in simplified version: Measure θ, the solar elevation angle, or alternatively, record the hour, minute and second of the data sampling and calculate the sun's elevation.

   8) Only required in simplified version: Record P, the local air pressure.

   9) Not required in simplified version: Repeat steps 1 to 6 several times.

   10) Only required in simplified version: Repeat steps 1 to 5, 7 and 8 at least every 5 min for several hours before and after solar noon, spanning the range of air mass from $AM < 1{,}5$ to $AM > 3{,}0$ in both time periods.

h) Repeat the whole measurement procedure on at least two other days.

A.2.4 Data analysis

For all data points taken, apply in sequence the following steps:

a) Reject data points where G_{dir}, G_{dif} or I_{sc} deviate by more than ±3 % when compared to the previous data point.

b) Calculate the total irradiance $G_{\text{T}} = G_{\text{dir}} + G_{\text{dif}}$.

c) Scale the measured short-circuit current I_{sc} of the PV reference device to be calibrated to G_{STC} according to Formula (A.1).

d) Correct for temperature according to Formula (A.2). This is normally not required as the temperature is maintained as described in A.2.3.d) and the allowed temperature deviation is accounted for in the uncertainty budget.

e) Correct for differences in spectral responsivity according to Formula (A.3), where $E_{meas}(\lambda)$ is the measured spectral irradiance of the global natural sunlight.

f) Calculate the calibration value according to Formula (A.4).

g) Average all calibration values for one day to obtain CV_1.

h) Repeat steps a) to g) for the other days of measurement runs to obtain CV_2, CV_3, .. CV_n accordingly.

i) Determine the arithmetic average of all n CV_i values analysed according to the above steps which yields the final calibration value for the PV reference device:

$$CV = \frac{\sum_{i=1}^{n} CV_i}{n} \tag{A.5}$$

j) In the simplified version steps e) to g) are replaced as follows:

1) Reject data points for which the ratio G_{dif}/G_T is either smaller than 0,1 or larger than 0,3. Also reject data points where G_T is outside the range G_{STC} ±20 %. This is to ensure that data used for the analysis are taken during atmospheric conditions close to the standard reference spectrum.

2) Using the sun's elevation angle and the atmospheric pressure, calculate the air mass (AM) at the moment of measurement according to:

$$AM = \frac{P}{P_0 \sin\theta} \tag{A.6}$$

3) Reject all data samples where $AM > 3$.

4) Plot the value of I_{sc} obtained after step d) versus the air mass value AM_i of each corresponding measurement sample.

5) By using a linear least-squares fit, calculate the slope (m) and offset (b) of the best fit straight line of the data set. In order to balance the fit, all short-circuit current readings should be averaged for AM bins of 0,01 before performing the fit. Both morning and afternoon have to contribute at least 33 % of the total number of measurement samples used for the least-squares fit. For a good straight line fit, 10 data points shall be considered as minimum. The more data points in the least-squares fit are close to AM = 1,5, the smaller the uncertainty of the procedure. It is permissible to use only data from half a day (morning or afternoon). However, in the final average, at least data from three different days with at least two mornings and two afternoons have to be included.

6) Calculate the calibration value of the PV reference device by the formula:

$$CV_1 = m \times AM + b \quad \text{with } AM = 1{,}5 \tag{A.7}$$

7) Perform steps h) and i).

A.2.5 Uncertainty estimates

In Table A.1, typical values of the uncertainty components for the global sunlight method (left column) and its simplified version (right column) are listed, resulting in combined expanded uncertainties U_{95} (with coverage factor k = 2) of 0,7 % and 0,8 % respectively.

Table A.1 – Typical uncertainty components (k = 2) of global sunlight method

Uncertainty in measurement of short-circuit current	< 0,1 %	
Uncertainty due to unstable device temperature (±2 K)	< 0,1 %	
Uncertainty of direct irradiance	< 0,25 %	
Uncertainty of diffuse irradiance	< 1,6 %	
Uncertainty of total irradiance (80 % direct and 20 % diffuse)	< 0,5 %	
Uncertainty of scale difference WRR versus SI	0,18 %	
Uncertainties due to correction with Formula A.3 or spectral irradiance deviations between test conditions and the reference spectral irradiance of AM1.5G (IEC 60904-3)	0,4 %	0,5 %
Combined expanded uncertainty	< 0,7 %	< 0,8 %

A.2.6 Reference documents

– IEC 60904-8: *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

– K.A. Emery, C.R. Osterwald, L.L. Kazmerski, and R.E. Hart, 1988c, "Calibration of Primary Terrestrial Reference Cells When Compared With Primary AM0 Reference Cells", *Proceedings of the 8th PV Solar Energy Conference*, Florence, pp. 64-68

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A.3 Differential spectral responsivity calibration (DSR)

A.3.1 General

Traceability is based on a calibration of spectral responsivity based on standard detectors directly traceable to SI units. The calibration value is computed from the measured absolute spectral responsivity of the PV reference device and the reference solar spectral irradiance distribution. The spectral responsivity calibration is transferred from the standard detector irradiance level to the solar irradiance level over many orders of magnitude with no restrictions to the PV reference device concerning linearity or spectral match.

A.3.2 Equipment

The following apparatus is required (see Figure A.1 and Figure A.2).

a) A monochromator producing chopped spectral irradiance within the wavelength range covering the spectral irradiance responsivity of the PV reference device to be calibrated, with a traceable wavelength setting.

b) Lamp(s) with lens or mirror entrance optics (recommended are quartz-halogen lamps to cover wavelengths above 400 nm; and xenon-arc lamps for wavelengths below 400 nm). Alternatively, a tuneable or white light cw-laser source with a continuously available spectral range covering the spectral irradiance responsivity of the PV reference device to be calibrated.

c) A bias light source, meeting in spectral irradiance, uniformity and temporal stability the requirements of class CBA as defined in IEC 60904-9.

d) A chopped monochromatic beam, traceable in its wavelength calibration, for the absolute calibration at one or more discrete wavelengths. The non-uniformity shall be smaller than ±3 % within the active area of the device to be calibrated.

   Comment: The monochromatic beam from A.3.2.a) can be used for this purpose if it fulfils the given requirement.

e) A monitor photodiode large enough to monitor the radiation power of the monochromatic beam of a) and d).

f) Optional: a standard spectroradiometer to monitor the wavelength of the monochromatic beam.

g) Standard spectral irradiance detector(s) with temperature control directly traceable to SI units. These detectors shall be photodiodes with the best available linearity, uniformity and stability.

h) Adjustable aperture (imaged onto the PV reference device);

i) Means for maintaining the temperature of the PV reference device at (25 ± 0,5) °C.

j) Means for measuring the AC short-circuit currents of the PV reference device, the standard detector(s) and the monitoring detector, for example with a lock-in amplifier. The variation of the amplification factor of such amplifiers shall be less than 0,1 % over the signal ranges used. Preferably the same amplifier and measurement range is used for the PV reference device and the standard detector.

k) Means for measuring the DC component of the PV reference device I_b as defined in step A.3.3.f).

A.3.3 Test procedure

a) Set and maintain the temperature of the PV reference device to (25 ± 0,2) °C. If larger temperature deviations occur, corrections have to be applied using the spectral temperature coefficient of the spectral irradiance responsivity.

b) Adjust the aperture until its image over-illuminates the whole PV reference device.

c) Mount the standard detector at the same position and plane where the PV reference device is calibrated.

d) Calibrate the monochromatic irradiance source of A.3.2.a) (without bias radiation) with respect to its relative spectral irradiance. Use the chopped monochromatic beam to determine the ratio of the AC short-circuit currents of the monitor photodiode ($\Delta I_{\text{mon,st}}(\lambda)$) and standard detector ($\Delta I_{\text{st}}(\lambda)$) which are measured simultaneously at wavelength intervals of not more than 10 nm over the whole responsivity range.

e) Set the white bias irradiance E_b to the desired operational level (between 10 Wm^{-2} and 1 500 Wm^{-2}) and measure the corresponding DC short-circuit current $I_b = I_{sc}(E_b)$ of the PV reference device. Ensure that the standard detector is protected from the white bias irradiance.

f) Measure the relative differential spectral irradiance responsivity of the PV reference device by using the chopped monochromatic radiation of irradiance source A.3.2.a) and determining the ratio of the short-circuit currents of PV reference device $(\Delta I_{\text{ref}}(\lambda, I_b))$ and monitor photodiode $(\Delta I_{\text{mon,ref}}(\lambda))$. Calculate the relative differential spectral irradiance responsivity $\tilde{s}(\lambda, I_b)_{\text{rel}}$ of the PV reference device under bias irradiance E_b:

$$\tilde{s}(\lambda, I_b)_{\text{rel}} = \frac{\Delta I_{\text{ref}}(\lambda, I_b)}{\Delta I_{\text{mon,ref}}(\lambda)} \frac{\Delta I_{\text{mon,st}}(\lambda)}{\Delta I_{\text{st}}(\lambda)} s_{\text{st}(\lambda)} \quad \text{(A.8)}$$

where $s_{\text{st}}(\lambda)$ is the spectral irradiance responsivity of the standard detector at wavelength λ.

– Comment: If a standard spectroradiometer for wavelength monitoring or correction is used (A.3.2.f) a wavelength correction shall be performed prior to the determination of $\tilde{s}(\lambda, I_b)_{\text{rel}}$.

g) Repeat steps e) and f) at five or more different bias levels covering at least the range between 10 Wm^{-2} and 1 100 Wm^{-2}, thus including a linearity test of relative spectral irradiance responsivity.

h) Calibrate the monochromatic irradiance source of A.3.2.d) (possibly in a different measurement plane with better uniformity) at one to three wavelengths λ_i (without bias radiation) with respect to its absolute spectral irradiance. Use the chopped monochromatic beam to determine the ratio of the AC short-circuit currents of the monitor photodiode $(\Delta I_{\text{mon,st}}(\lambda_i))$ and standard detector $(\Delta I_{\text{st}}(\lambda_i))$ which are measured simultaneously.

i) Set the white bias irradiance to a low level E_0 near to or at the minimum as specified in step e) and measure the corresponding DC short-circuit current $I_0 = I_{sc}(E_0)$ of the PV reference device. Ensure that the standard detector is protected from the white bias irradiance.

j) Measure the absolute differential spectral irradiance responsivity of the PV reference device at one to three wavelengths λ_i by using the chopped monochromatic radiation of irradiance source in A.3.2.d) and determining the ratio of the short-circuit currents of PV reference device $(\Delta I_{\text{ref}}(\lambda_i, I_0))$ and monitor photodiode $(\Delta I_{\text{mon,ref}}(\lambda_i))$. Calculate the absolute differential spectral irradiance responsivity $\tilde{s}(\lambda_i, I_0)$ of the PV reference device under bias irradiance E_0:

$$\tilde{s}(\lambda_i, I_0) = \frac{\Delta I_{\text{ref}}(\lambda_i, I_0)}{\Delta I_{\text{mon,ref}}(\lambda_i)} \frac{\Delta I_{\text{mon,st}}(\lambda_i)}{\Delta I_{\text{st}}(\lambda_i)} s_{\text{st}(\lambda_i)} \quad \text{(A.9)}$$

where $s_{\text{st}(\lambda_i)}$ is the spectral irradiance responsivity of the standard detector at wavelength λ_i.

– Comment: If a standard spectroradiometer for wavelength monitoring or correction is used (A.3.2.f) a wavelength correction shall be performed prior to the determination of $\tilde{s}(\lambda_i, I_0)$.

– Comment: If the monochromatic beam of A.3.2.a) is used for the absolute calibration of the complete differential spectral irradiance responsivity of the PV reference device, the calibration of the monochromatic irradiance source in A.3.3.d) is performed with respect to its absolute spectral irradiance. Subsequently the absolute differential spectral irradiance responsivity of the PV reference device $\tilde{s}(\lambda, I_b)$ instead of its relative differential spectral irradiance responsivity $\tilde{s}(\lambda, I_{\mathrm{b}})_{\mathrm{rel}}$ is obtained in step A.3.3.f) and steps A.3.3.h), A.3.3.i) and A.3.3.j) can be omitted.

A.3.4 Data analysis

a) Calculate the ratio $k_i(\lambda_i)$ = (relative spectral irradiance responsivity as determined in A.3.3.f)/(absolute spectral irradiance responsivity as determined in A.3.3.j) for each of the three wavelengths λ_1, λ_2, λ_3 under the E_0 irradiation. All three $k_i(\lambda_i)$ values shall be within a range of ±0,5 % of the average of the three values, otherwise measurements shall be repeated until fulfilled. All measurement uncertainties shall be correctly assigned to the k_i values and the relative DSR. Then the uncertainties of the k_i values shall be propagated through the averaging, taking correlations into account. The combined standard uncertainty shall be larger than the standard deviation of the average of the three $k_i(\lambda_i)$ values, since the standard deviation reflects the uncorrelated measurements uncertainties and the reproducibility of the absolute differential spectral responsivity measurement.

b) Compute the absolute differential spectral responsivities by scaling the relative responsivity with the mean value of the k_i determined in step a):

$$\tilde{s}(\lambda, I_{\mathrm{b}}) = \tilde{s}(\lambda, I_{\mathrm{b}})_{\mathrm{rel}} \frac{k_1 + k_2 + k_3}{3} \tag{A.10}$$

c) Compute the differential responsivity $s_{\mathrm{AM1.5G}}(I_{\mathrm{b}})$ under irradiation with $E_{\mathrm{ref}}(\lambda)$ for at least five different levels of bias light determined by I_{b}:

$$s_{\mathrm{AM1.5G}}(I_{\mathrm{b}}) = \frac{\int \tilde{s}(\lambda, I_{\mathrm{b}}) E_{\mathrm{ref}}(\lambda)\, d\lambda}{G_{\mathrm{STC}}} \tag{A.11}$$

with

$$G_{\mathrm{STC}} = \int E_{\mathrm{ref}}(\lambda)\, d\lambda = 1000 \frac{W}{m^2} \tag{A.12}$$

and

$$I_{\mathrm{b}} = I_{\mathrm{sc}}(E_{\mathrm{b}}) \tag{A.13}$$

d) The calibration value of the short-circuit current under STC conditions I_{STC} is calculated from the following formula:

$$E_{\mathrm{STC}} = \int_0^{I_{\mathrm{STC}}} \frac{1}{s_{\mathrm{AM1.5G}}(I_{\mathrm{b}})} dI_{\mathrm{b}} \tag{A.14}$$

where the upper integration limit I_{STC} is obtained by iterative approximation. Refer to IEC 60904-10 for determination of whether the PV reference device can be considered linear.

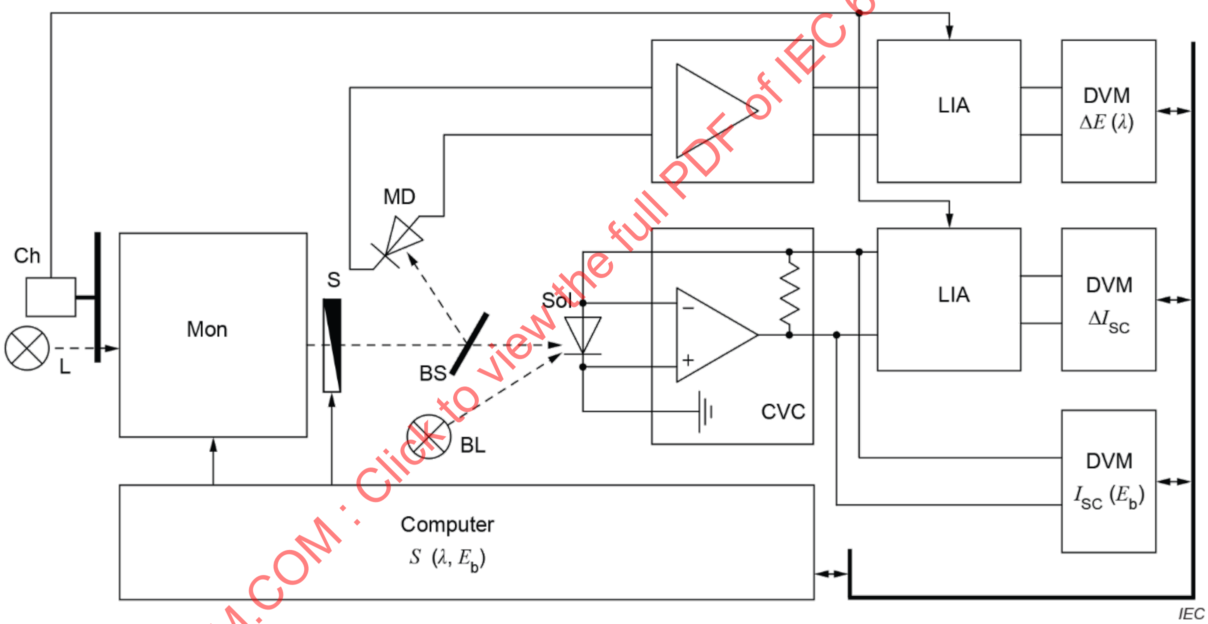
A.3.5 Uncertainty estimate

In Table A.2, typical values of the uncertainty components resulting in a combined expanded uncertainty of $U_{95} < 0,5$ % (with coverage factor k = 2) are summarized.

NOTE The uncertainty quoted is not easily achieved and might only be available at some national metrological institutes.

Table A.2 – Uncertainty components (k = 2) of differential spectral responsivity calibration method on PV reference devices

Uncertainty due to unstable device temperature (±0,5 K)	0,1 %
Uncertainty of the standard detector(s)	0,2 %
Uncertainty due to nonlinear and/or narrow-band devices	0,1 %
Transfer uncertainties (repeatability) due to relative spectral responsivity	0,1 %
Transfer uncertainties (repeatability) due to absolute spectral responsivity at discrete wavelength(s)	0,1 %
Spectral mismatch between bias radiation and reference solar spectrum; non-uniformity of bias radiation; non-uniformity of monochromatic radiation; mismatch of device area and irradiated area (image of the aperture); spectral bandwidth (< 11 nm) of the monochromatic radiation; nonlinearity of the amplifiers; determination of reference plane of standard detector and PV reference device, wavelength calibration and reproducibility of the monochromatic light source	0,4 %
Combined expanded uncertainty	0,5 %
In this table, typical values on the uncertainty components resulting in a combined expanded uncertainty of U_{95} < 0,5 %, with coverage factor k = 2, are summarized. It is not required that the PV reference device is linear, and there are no restrictions on the shape of the spectral responsivity curve of the device; however, temperature control of the device within ±1 K is recommended.	



Key

Mon monochromator

Ch chopper

L light source with entrance optics

S shutter

BS beam splitter

MD monitor photodiode

BL (array of) bias lamp(s)

Sol PV device and standard detector respectively

CVC current-voltage converter

LIA lock-in amplifier

DVM digital voltmeter

Figure A.1 – Block diagram of differential spectral responsivity calibration superimposing chopped monochromatic radiation $DE(l)$ and DC bias radiation E_b

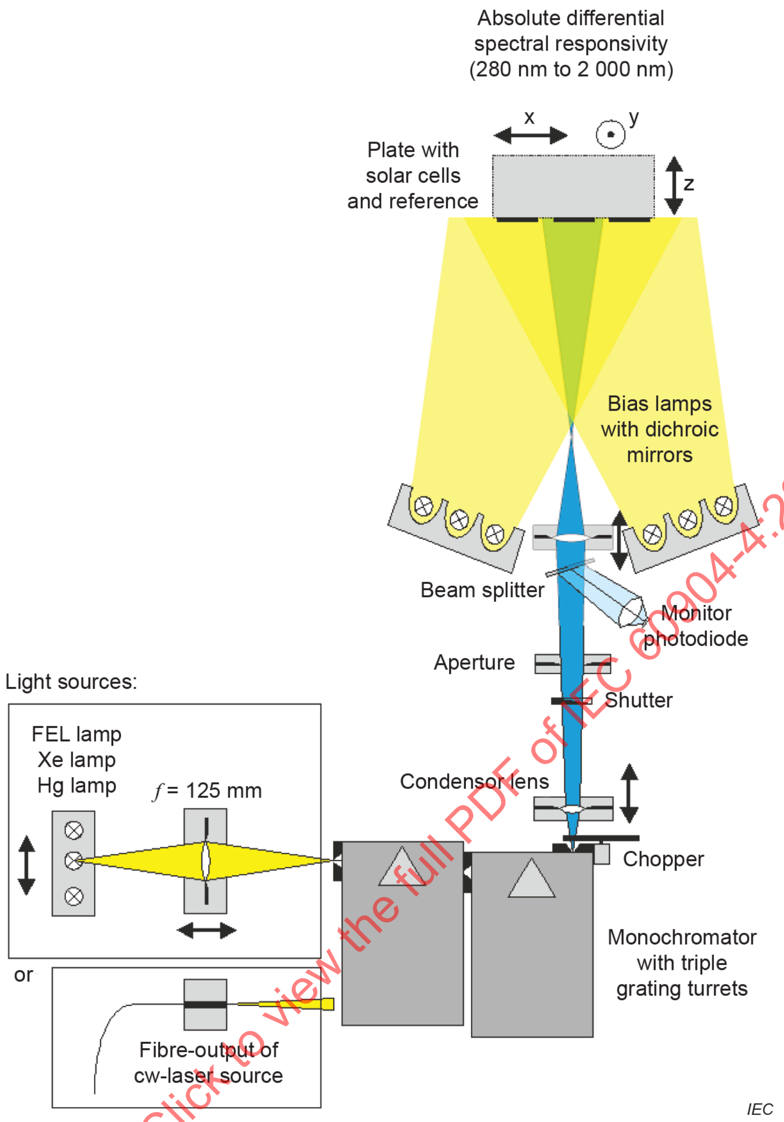


Figure A.2 – Optical arrangement of differential spectral responsivity calibration

A.3.6 Reference documents

- IEC 60904-9: *Photovoltaic devices – Part 9: Solar simulator performance requirements*
- IEC 60904-10: *Photovoltaic devices – Part 10: Methods of linearity measurements*
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A.4 Solar simulator method (SSM)

A.4.1 General

Traceability is based on the absolute spectral irradiance of simulated sunlight and relative spectral responsivity of the PV reference device to be calibrated. The absolute spectral irradiance shall be measured by a spectroradiometer calibrated by standard lamps directly traceable to SI units, and the spectral responsivity shall be calibrated by standard detectors directly traceable to SI units. When traceability via WRR is required, the absolute irradiance of the solar simulator shall be measured by using a cavity radiometer traceable to the WRR. The calibration value is computed from the measured spectral responsivity of the PV reference device, the spectral irradiance distribution of the solar simulator and the reference solar spectral irradiance distribution (IEC 60904-3).

A.4.2 Equipment

The following apparatus is required (see Figure A.3).

a) A solar simulator of class AAA as defined in IEC 60904-9. The uncertainty analysis below assumes that spatial non-uniformity of irradiance is below 0,2 % and temporal instability is below 0,1 %. When the cavity radiometer (A.4.2.e) is used the solar simulator shall be steady-state with collimated light beam.

b) A spectroradiometer as described in CIE 53-1982.

c) Means for measuring relative spectral responsivity of the PV reference device as defined in IEC 60904-8.

d) A standard lamp which has been directly calibrated by the primary standard lamps, which shall be mutually recognized and authorized by CCPR/CIE.

e) A cavity radiometer traceable to the WRR whose view angle is wider than the spreading angle of the solar simulator light (optional).

f) Means for measuring the short-circuit current of the PV reference device which shall comply with the general measurement requirements of IEC 60904-1.

g) Means for maintaining the temperature of the PV reference device at (25 ± 2) °C if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval.

A.4.3 Calibration procedure

a) The relative spectral responsivity of the PV reference device shall be measured in accordance with IEC 60904-8.

b) The irradiance of the solar simulator in the test plane shall be set to approximately G_{STC}, using a thermal photo detector such as a thermopile.

c) The absolute spectral irradiance distribution in the test plane shall be measured by the calibrated spectroradiometer as described in CIE 63-1984. For the calculation as described in A.4.4 a) the wavelength range has to span at least the same interval as $s(\lambda)$. When the cavity radiometer is used as in A.4.4. b), the wavelength range of the spectral irradiance measurement shall be sufficiently large to reach the desired uncertainty.

d) The PV reference device shall be located in the test plane of the simulator. The device temperature shall be maintained at (25 ± 2)°C throughout all calibration runs if temperature corrections are not applied. The temperature should be stable within 0,5 °C during the data collection interval. The short-circuit current of the device is to be measured more than 10 times and the mean value is to be calculated.

A.4.4 Data analysis

a) The calibration value (CV) is to be computed as follows.

$$CV = I_{SC} \frac{\int_0^\infty E_{\text{ref}}(\lambda) s(\lambda) d\lambda}{\int_0^\infty E_{\text{meas}}(\lambda) s(\lambda) d\lambda} \tag{A.15}$$

where:

$E_{\text{meas}}(\lambda)$ is the absolute spectral irradiance distribution of the solar simulator.

b) When direct traceability to WRR is required, the absolute irradiance of the solar simulator shall be measured by using a cavity radiometer traceable to the WRR, as described in A.4.2.e). The calibration value (CV) is computed according to Formula (A.4). G_{T} is the total irradiance of the solar simulator measured by the cavity radiometer.

c) Repeating the steps in A.4.3. and A.4.4 twice, the mean CV is to be calculated as the final calibration value.

A.4.5 Uncertainty estimate

In the following Tables A.3 and A.4, typical values of the uncertainty components resulting in combined expanded uncertainty of U_{95} of 2 % and 0,6 % (with coverage factor k = 2) are summarized.

Table A.3 – Example of uncertainty components (k = 2) of a solar simulator method calibration

Uncertainty of the standard lamp:	< 2 %
Uncertainty due to spectroradiometer:	< 0,2 %
Uncertainty due to unstable device temperature:	< 0,2 %
Transfer uncertainties due to spectral responsivity, spectral mismatch between solar simulator and reference solar spectrum:	< 0,2 %
Uncertainty due to temporal and spatial non-uniformity of solar simulator and different size and time constant of spectroradiometer and device:	< 0,2 %
Combined expanded uncertainty	2 %

Table A.4 – Typical uncertainty components (k = 2) of a solar simulator method calibration when WRR traceable cavity radiometer is used

Uncertainty of WRR versus SI units	0,18 %
Uncertainty of irradiance measurement	< 0,2 %
Uncertainty due to unstable device temperature:	< 0,2 %
Uncertainties due to spectral irradiance deviations between test conditions and the reference spectral irradiance of AM1.5G (IEC 60904-3) or spectral mismatch correction (IEC 60904-7)	< 0,3 %
Uncertainty due to temporal and spatial non-uniformity of solar simulator and different size and time constant of spectroradiometer, device and cavity radiometer:	< 0,2 %
Combined expanded uncertainty	0,6 %

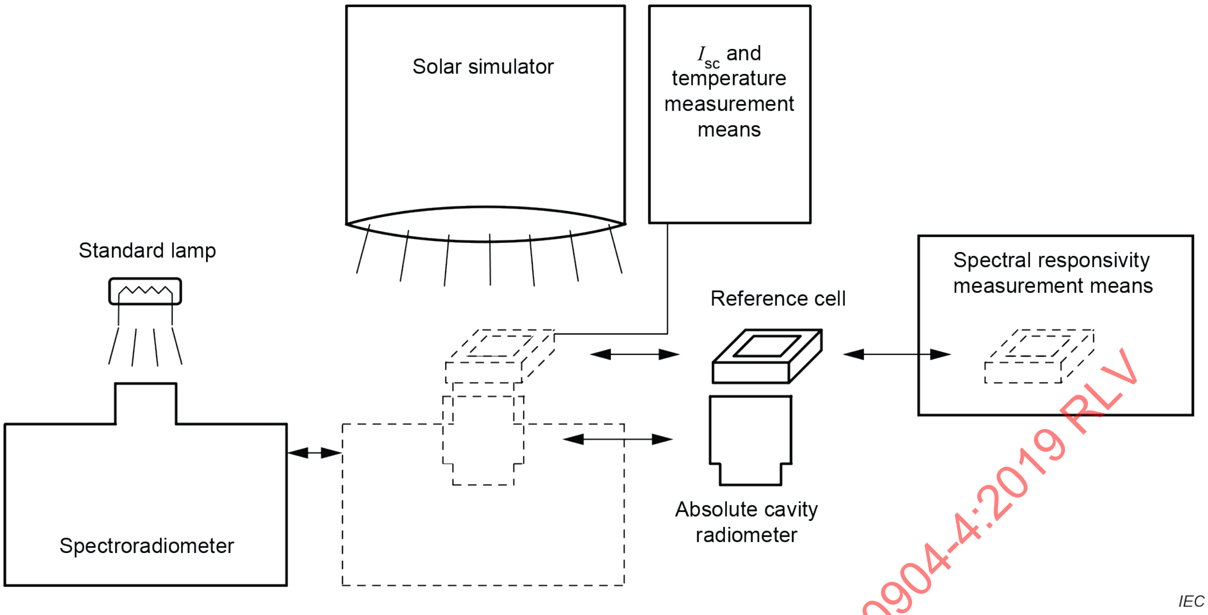

Figure A.3 – Schematic apparatus of the solar simulator method

A.4.6 Reference documents

– IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

– IEC 60904-8: *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

– IEC 60904-9: *Photovoltaic devices – Part 9: Solar simulator performance requirements*

– R. Shimokawa, F. Nagamine, Y. Miyake, K. Fujisawa, Y. Hamakawa, “Japanese indoor calibration method for the reference solar cell and comparison with outdoor calibration”, *Japanese J. Appl. Phys.* **26**(1), 1987, 86-91

– R. Shimokawa, H. Ikeda, Y. Miyake, S. Igari, "Development of wide field-of-view cavity radiometer for solar simulator use and intercomparison between irradiance measurements based on the world radiometer reference and electrotechnical laboratory scales", *Japanese J. Appl. Phys.* **41,** 2002, 5088-5093

– H. Müllejans, W. Zaaiman, F. Merli, E. D. Dunlop, H. A. Ossenbrink, “Comparison of traceable calibration methods for primary photovoltaic reference cells”, *Progress in Photovoltaics* **13,** 2005, 661-671

– CIE 53-1982, *Methods of Characterizing the Performance of radiometers and Photometers*, ISBN 92 9034 053 3

– CIE 63-1984, *The Spectroradiometric Measurement of Light Sources*

A.5 Direct sunlight method (DSM)

A.5.1 General

The PV reference device to be calibrated is compared under direct-beam natural sunlight with a reference radiometer. The establishment of traceability is based on the calibration using a pyrheliometer measuring direct solar irradiance and traceable to the WRR. The short-circuit current of the PV reference device is measured, scaled to G_{STC} and corrected for temperature and spectral mismatch between the direct-beam natural sunlight spectrum as measured by a spectroradiometer and the defined standard spectrum (IEC 60904-3). The relative spectral responsivity of the PV reference device also has to be determined according to IEC 60904-8.

A.5.2 Equipment

a) A mounting platform, which can be oriented normal to the sun within an accuracy of ±0,5° throughout the calibration run.

b) A cavity radiometer, traceable to the WRR.

c) A collimator tube for the PV reference device having the same viewing angle as the cavity radiometer.

d) A temperature-controlled mounting block for the PV reference device to be calibrated capable of maintaining the junction temperature at (25 ± 2) °C throughout all calibration runs if temperature corrections are not applied. The uncertainty analysis assumes that temperature corrections are applied and the temperature is stable within 0,2 °C during the data collection interval.

e) Traceable means to measure the short-circuit current of the PV reference device to an accuracy of ±0,1 % or better.

f) A spectroradiometer for measuring the direct normal solar spectral irradiance with the same viewing angle as the cavity radiometer.

g) An apparatus to measure the relative spectral responsivity of the PV reference device according to IEC 60904-8 and as a function of temperature.

A.5.3 Measurements

A calibration according to this document shall be performed only on clear, sunny days with no visible cloud cover within 30° of the sun.

a) Mount the PV reference device to be calibrated with the collimator, the cavity radiometer, and the spectroradiometer coplanar on the tracking platform.

b) Measure the relative spectral irradiance of the sun, $E_{\text{meas}}(\lambda)$, using the spectroradiometer. During the spectral irradiance measurement, perform the following steps simultaneously:

   1) Measure the cavity radiometer output, G_{dir}, and verify that the irradiance is between 750 Wm^{-2} and 1 100 Wm^{-2}.

   2) Measure the short-circuit current I_{SC} of the PV reference device to be calibrated.

   3) Measure the PV reference device temperature, T_{j}.

   4) Repeat these steps at least four times. These repetitions shall be distributed in time during a single spectral irradiance measurement.

c) Perform a minimum of five replications of step b) on at least three separate days.

A.5.4 Data analysis

a) Perform the correction of Formula (A.1), where G_{T} is the reading of the cavity radiometer representing the direct irradiance G_{dir}.

b) Average the calibration values from a) for each measurement of spectral irradiance.

c) Correct the data to 25 °C and translate the data to the reference spectrum.

   Correct each result of step b) for temperature and spectral effect according to Formula (A.16) giving one CV_i according to Formula (A.17).

$$F(T_{\text{j}}) = \frac{\int_0^\infty E_{\text{ref}}(\lambda)\,d\lambda}{\int_0^\infty E_{\text{meas}}(\lambda)\,d\lambda} \cdot \frac{\int_0^\infty E_{\text{meas}}(\lambda)\left[s(\lambda, 25\ °\text{C}) + (T_{\text{j}} - 25\ °\text{C})\dfrac{\partial s(\lambda, T_{\text{j}})}{\partial T}\right]d\lambda}{\int_0^\infty E_{\text{ref}}(\lambda)\,s(\lambda, 25\ °\text{C})\,d\lambda} \tag{A.16}$$

$$CV_i = I_{\text{SC}}\frac{M_{\text{G}}}{F(T_{\text{j}})} \tag{A.17}$$

d) Average all CV_i for each day and calculate the arithmetic average CV using Formula (A.5).

e) Reject any points that meet the following criteria:

   1) CV_i more than 1,5 % from CV;

   2) I_{SC} range is greater than 1,5 %;

   3) $CV_i\ (T_j)$ standard deviation is $>$ 1 %.

f) Verify that at least three days data with a minimum of five sets per day of valid data exist. If not take additional measurements until this criterion is met. Typically five days of data with 10 sets per day of valid data are used obtained to further reduce the standard deviation of CV.

A.5.5 Uncertainty estimate

In Table A.5, typical values of the uncertainty components for the direct sunlight method are listed, resulting in combined expanded uncertainty U_{95} (with coverage factor $k = 2$) of 0,6 %.

Table A.5 – Typical uncertainty components (k = 2) of a direct sunlight method using temperature dependent spectral correction factor (Formula (A.16)), without applying a correction factor for the WRR to SI scale

Uncertainty of scale difference WRR versus SI	0,34 %
Measured direct irradiance	< 0,18 %
Spectral mismatch correction	0,05 %
Uncertainty due to device temperature correction	< 0,1 %
Combined expanded uncertainty	0,46 %

A.5.6 Reference documents

– IEC 60904-8: *Photovoltaic devices – Part 8: Measurement of spectral responsivity of a photovoltaic (PV) device*

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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DISPOSITIFS PHOTOVOLTAÏQUES –

Partie 4: Dispositifs photovoltaïques de référence – Procédures pour établir la traçabilité de l'étalonnage

AVANT-PROPOS

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La Norme internationale IEC 60904-4 a été établie par le comité d'études 82 de l'IEC: Systèmes de conversion photovoltaïque de l'énergie solaire.

Cette deuxième édition annule et remplace la première édition parue en 2009. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) modification du titre de la norme;
b) incorporation de la référence de travail à la chaîne de traçabilité;
c) mise à jour de la WRR (*world radiometric reference* – référence radiométrique mondiale) par rapport au SI;

d) révision de toutes les méthodes et de leurs incertitudes à l'Annexe A:

e) harmonisation des symboles et formules avec les autres normes IEC.

Le texte de cette Norme internationale est issu des documents suivants:

FDIS	Rapport de vote
82/1618/FDIS	82/1638/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2

Une liste de toutes les parties de la série IEC 60904, publiées sous le titre général *Dispositifs photovoltaïques*, peut être consultée sur le site web de l'IEC.

Le comité a décidé que le contenu de ce document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous «http://webstore.iec.ch» dans les données relatives au document recherché. À cette date, le document sera

- reconduit,
- supprimé,
- remplacé par une édition révisée, ou
- amendé.

Le contenu du corrigendum de septembre 2020 a été pris en considération dans cet exemplaire.

IMPORTANT – Le logo «colour inside» qui se trouve sur la page de couverture de cette publication indique qu'elle contient des couleurs qui sont considérées comme utiles à une bonne compréhension de son contenu. Les utilisateurs devraient, par conséquent, imprimer ce document en utilisant une imprimante couleur.

DISPOSITIFS PHOTOVOLTAÏQUES –

Partie 4: Dispositifs photovoltaïques de référence – Procédures pour établir la traçabilité de l'étalonnage

1 Domaine d’application

La présente partie de l’IEC 60904 fixe les exigences relatives aux procédures d'étalonnage dans le but d'établir la traçabilité des dispositifs photovoltaïques (PV) de référence en unités SI, comme cela est exigé par l’IEC 60904-2.

Le présent document s'applique aux dispositifs PV de référence utilisés pour mesurer l'éclairement énergétique de la lumière solaire naturelle ou simulée afin de quantifier les performances des dispositifs PV. L'utilisation d'un dispositif PV de référence est exigée dans de nombreuses normes relatives aux dispositifs PV (par exemple, l’IEC 60904-1 et l’IEC 60904-3).

Le présent document a été rédigé en prenant en considération les dispositifs PV de référence à jonction unique, en particulier le silicium cristallin, mais il est suffisamment général pour inclure d’autres technologies à jonction unique.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu’ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l’édition citée s’applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60904-1, *Dispositifs photovoltaïques – Partie 1: Mesure des caractéristiques courant-tension des dispositifs photovoltaïques*

IEC 60904-2, *Dispositifs photovoltaïques – Partie 2: Exigences applicables aux dispositifs photovoltaïques de référence*

IEC 60904-3, *Dispositifs photovoltaïques – Partie 3: Principes de mesure des dispositifs solaires photovoltaïques (PV) à usage terrestre incluant les données de l'éclairement énergétique spectral de référence*

IEC TS 61836, Solar photovoltaic energy systems – Terms, definitions and symbols (disponible en anglais seulement)

Guide ISO/IEC 98-3: 2008, *Incertitude de mesure – Partie 3: Guide pour l’expression de l’incertitude de mesure (GUM: 1995)*

3 Termes et définitions

Pour les besoins du présent document, les termes et définitions de l’IEC TS 61836 ainsi que les suivants s'appliquent.

NOTE Les différents appareils de référence liés à la chaîne de traçabilité de l'éclairement énergétique solaire sont définis dans le présent article. Des exemples types pour chaque catégorie sont énumérés dans le Tableau 1, qui renvoie également aux normes pertinentes (lorsqu’elles sont disponibles). La Figure 1 décrit ensuite schématiquement les chaînes de traçabilité les plus courantes reliant ces instruments et les normes pertinentes (si elles sont disponibles). L'Annexe A décrit les méthodes pour la mise en œuvre du présent document.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
étalon primaire
étalon qui est désigné ou largement reconnu comme présentant les plus hautes qualités métrologiques et dont la valeur est établie sans se référer à d'autres étalons de la même grandeur

Note 1 à l'article: Le concept d'étalon primaire est valable aussi bien pour les grandeurs de base que pour les grandeurs dérivées.

Note 2 à l'article: Un étalon primaire n'est jamais utilisé directement pour des mesurages en dehors de sa comparaison avec les étalons témoins ou avec des étalons de référence.

Note 3 à l'article: Les étalons primaires sont habituellement maintenus par les instituts nationaux de métrologie (INM) ou par des organisations similaires qui ont la responsabilité de l'entretien des étalons relatifs aux grandeurs physiques. Souvent également désignée par le seul terme «primaire», la mise en œuvre physique est choisie de telle sorte que la stabilité à long terme, l'exactitude et la répétabilité du mesurage de la grandeur qu'il représente soient garanties aussi largement que possible par la technologie actuelle.

Note 4 à l'article: La référence radiométrique mondiale (WRR), représentée par le groupe étalon mondial (GEM) composé de radiomètres à cavité, est l'étalon primaire admis pour le mesurage de l'éclairement énergétique solaire.

3.2
étalon secondaire
dispositif qui, par comparaison périodique avec l'étalon primaire, sert à maintenir la conformité, en unités SI, en d'autres lieux que celui où se trouve l'étalon primaire

Note 1 à l'article: Un étalon secondaire n'emploie pas nécessairement les mêmes principes techniques que l'étalon primaire, mais s'efforce d'obtenir une stabilité à long terme, une exactitude et une répétabilité similaires.

Note 2 à l'article: Les étalons secondaires types pour l'éclairement énergétique solaire sont les radiomètres à cavité, qui participent périodiquement (généralement tous les 5 ans) à la comparaison internationale des pyrhéliomètres (IPC – *International Pyrheliometer Comparison*) avec le GEM, permettant ainsi de garantir la traçabilité par rapport à la WRR. La traçabilité directe par rapport à l'échelle radiométrique SI peut également être disponible pour ces appareils.

3.3
référence primaire
appareil qu'un laboratoire utilise pour étalonner des références secondaires périodiquement par rapport à un étalon secondaire

Note 1 à l'article: Les références primaires peuvent souvent être réalisées à des coûts bien inférieurs à ceux des étalons secondaires.

Note 2 à l'article: Généralement, une cellule PV est utilisée comme dispositif de référence pour le mesurage de l'éclairement énergétique solaire naturel ou simulé. Les références primaires sont généralement utilisées par les laboratoires d'étalonnage et d'essais.

3.4
référence secondaire
dispositif de mesure utilisé pour les mesurages de routine quotidiens ou pour étalonner des références de travail, lui-même étalonné périodiquement par rapport à une référence primaire

Note 1 à l'article: Les références secondaires les plus courantes destinées au mesurage de l'éclairement énergétique solaire naturel ou simulé sont les cellules PV et les modules PV. Les références secondaires sont généralement utilisées par les laboratoires d'étalonnage et d'essais, et parfois aussi dans la production industrielle.

3.5
référence de travail
dispositif de mesure utilisé pour les mesurages de routine quotidiens, étalonné périodiquement par rapport à une référence secondaire

Note 1 à l'article: Les références de travail les plus courantes destinées au mesurage de l'éclairement énergétique solaire naturel ou simulé sont les cellules PV et les modules PV.

Note 2 à l'article: Les références de travail sont généralement utilisées dans la production industrielle.

3.6
traçabilité ()
<d'un dispositif PV de référence> exigence, pour tout dispositif PV de référence, de lier sa valeur d'étalonnage en unités SI dans une chaîne ininterrompue et documentée de transferts d'étalonnage comprenant les incertitudes établies

Note 1 à l'article: La WRR a été comparée plusieurs fois à l'échelle radiométrique SI. Tandis que lors des comparaisons précédentes les deux échelles se sont révélées impossibles à distinguer dans l'incertitude de la comparaison, la dernière comparaison des échelles a démontré qu'il existe un décalage systématique entre les échelles, la WRR ayant un éclairement énergétique supérieur de 0,34 % à l'échelle SI. L'incertitude de ce décalage a été donnée à 0,18 % (k = 2). Par conséquent, la traçabilité par rapport à la WRR donne automatiquement la traçabilité en unités SI. Cependant, le décalage entre les échelles peut être corrigé pour les mesurages traçables par rapport à la WRR. L'incertitude de la comparaison des échelles doit être incluse dans le bilan d'incertitude. Il existe essentiellement deux possibilités pour le mesurage de la traçabilité en unités SI par le biais de la WRR. Premièrement, aucune correction n'est appliquée à la différence d'échelle, et une incertitude plus grande de 0,3 % (répartition rectangulaire) doit être utilisée. Deuxièmement, une correction nette de la différence d'échelle qui s'élève à 0,34 %. Dans ce cas, la contribution à l'incertitude est de 0,18 % (k = 2). La valeur de différence d'échelle de 0,34 % est la valeur disponible la plus récente au moment de la publication du présent document. Il convient de consulter les ouvrages scientifiques de référence pour vérifier les mises à jour éventuelles de la différence et de son incertitude. Il est possible notamment qu'à l'avenir la WRR soit adaptée à la prise en compte de cette différence et puisse l'adapter en unités SI. Dans ce cas, aucune correction supplémentaire ne doit être appliquée.

[SOURCE: A Fehlmann, G Kopp, W Schmutz, R Winkler, W Finsterle, N Fox, *metrologia* **49** (2012) S34]

Tableau 1 – Exemples d'appareils de référence utilisés dans une chaîne de traçabilité de l'éclairement énergétique solaire

Instrument de référence	Éclairement énergétique solaire
Étalon primaire	Groupe de radiomètres à cavité constituant le groupe étalon mondial (GEM) de la référence radiométrique mondiale (WRR) Détecteur de piège cryogénique Lampe normalisée
Étalon secondaire	Radiomètres à cavité disponibles dans le commerce comparés régulièrement (généralement tous les 5 ans), selon la comparaison internationale des pyrhéliomètres (IPC) Détecteur normalisé, étalonné par rapport à un détecteur de piège Spectroradiomètre étalonné par rapport à une lampe normalisée
Référence primaire	Pyrhéliomètre à incidence normale (NIP – *normal incidence pyrheliometer*) (ISO 9059) Dispositif PV de référence (IEC 60904-2 et IEC 60904-4)
Référence secondaire	Pyranomètre (ISO 9846) Dispositif PV de référence (IEC 60904-2)
Référence de travail	Pyranomètre (ISO 9847) Dispositif PV de référence (IEC 60904-2)

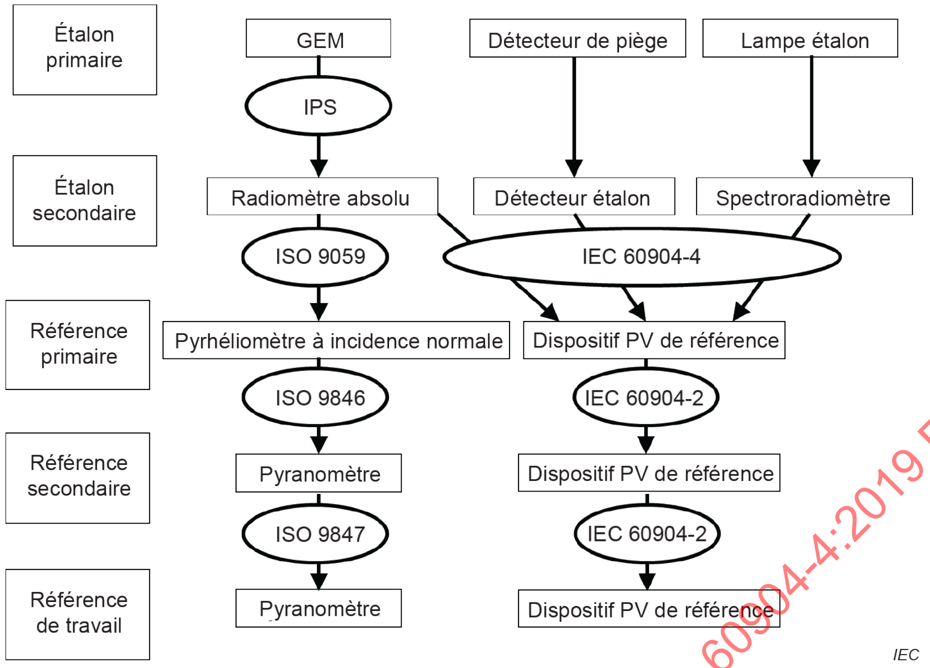

Figure 1 – Schéma des appareils de référence les plus courants et méthodes habituelles de transfert utilisées dans les chaînes de traçabilité, pour les détecteurs d'éclairement énergétique solaire

4 Exigences relatives aux procédures d'étalonnage traçables des dispositifs PV de référence

Une procédure d'étalonnage traçable est nécessaire pour transférer l'étalonnage d'un étalon ou d'une référence mesurant l'éclairement énergétique solaire et reposant sur un principe physique autre que l'effet PV (tel qu'un radiomètre à cavité, un pyrhéliomètre et un pyranomètre) à un dispositif PV de référence. Les exigences relatives à ces procédures sont les suivantes:

a) Tout appareil de mesure exigé et utilisé dans la procédure de transfert doit être un appareil dont la chaîne de traçabilité est ininterrompue.

b) Une analyse d'incertitude documentée.

c) Une répétabilité documentée, comme des résultats de mesure d'intercomparaison de laboratoires, ou des documents de contrôle qualité de laboratoires.

d) Une exactitude absolue inhérente, donnée par un nombre limité de transferts intermédiaires.

Habituellement, le transfert est réalisé d'un étalon secondaire à un dispositif PV de référence, constituant une référence primaire.

Le transfert d'un dispositif PV de référence à l'autre est couvert par l'IEC 60904-2.

5 Analyse de l'incertitude

Une estimation de l'incertitude conformément au Guide ISO/IEC 98-3: 2008 doit être assurée pour chaque procédure d'étalonnage traçable. Cette estimation doit fournir des informations sur l'incertitude de la procédure d'étalonnage, ainsi que des données quantitatives relatives aux facteurs d'incertitude suivants, pour chaque appareil utilisé pour exécuter la procédure d'étalonnage. Plus particulièrement:

a) La composante de l'incertitude résultant des effets aléatoires (Type A).

b) La composante de l'incertitude résultant des effets systématiques (Type B).

Une analyse complète de l'incertitude doit être réalisée pour la mise en œuvre de la méthode d'étalonnage par un laboratoire particulier. L'Annexe A donne des exemples des composantes principales de l'incertitude dans certaines mises en œuvre particulières. En raison de la diversité des méthodes disponibles, il est impossible de fournir des recommandations détaillées sur la manière dont il convient de réaliser une analyse de l'incertitude spécifique. Néanmoins, les composantes ci-dessous doivent être prises en considération:

– incertitude de tous les instruments de mesure utilisés;
– décalage et dérive de tous les instruments de mesure;
– incertitude de toutes les références utilisées;
– incertitude sur la température du dispositif mesuré;
– incertitude introduite par les écarts entre la température réelle et la température nominale du dispositif;
– incertitude de mesure de l'éclairement énergétique (éclairement énergétique total et spectral);
– incertitude introduite par les écarts entre l'éclairement énergétique spectral réel et l'éclairement énergétique spectral de référence;
– contributions dues à la répétabilité et la reproductibilité;
– Incertitude due à l'instabilité des conditions et des instruments.

6 Rapport d'étalonnage

Le rapport d'étalonnage doit inclure au moins les informations suivantes:

a) le titre (par exemple, «Certificat d'étalonnage»);
b) le nom et l'adresse du laboratoire, ainsi que du lieu où les étalonnages ont été effectués s'ils sont différents de l'adresse du laboratoire;
c) l'identification unique du rapport (telle que le numéro de série) et de chaque page, le nombre total de pages et la date d'émission;
d) le nom et l'adresse du client qui a passé la commande;
e) la description et l'identification non ambiguë de l'unité ou des unités étalonnées;
f) la date de réception de l'unité ou des unités d'étalonnage et la ou les dates d'étalonnage, s'il y a lieu;
g) les résultats de l'étalonnage et leurs incertitudes, y compris la température du dispositif sur lequel l'étalonnage a été réalisé;
h) la référence aux procédures d'échantillonnage employées par le laboratoire, lorsque celles-ci sont pertinentes vis-à-vis de la validité ou de l'application des résultats;
i) le ou les noms, le ou les titres et la ou les signatures, ou une identification équivalente de la ou des personnes autorisant la publication du rapport;
j) le cas échéant, une indication selon laquelle les résultats ne se rapportent qu'aux unités étalonnées;
k) le cas échéant, la sensibilité spectrale du dispositif PV de référence;
l) le cas échéant, le coefficient de température du dispositif PV de référence.

7 Marquage

Le dispositif PV de référence étalonné doit être identifié par un numéro de série ou par un numéro de référence, et les informations suivantes doivent être jointes ou fournies sur un certificat l'accompagnant:

a) la date de l'étalonnage (déjà réalisé ou en cours de réalisation);

b) la valeur d’étalonnage et son incertitude;

c) l’identification du laboratoire qui a réalisé l’étalonnage.

Annexe A
(informative)

Exemples de procédures d'étalonnage validées

A.1 Généralités

A.1.1 Vue d'ensemble

L'Annexe A décrit, à titre d'exemple, des procédures d'étalonnage applicables à des dispositifs PV de référence, en tant que dispositifs de référence primaire, ainsi que leurs incertitudes déclarées. Ces procédures ont pour but d'établir la traçabilité des dispositifs PV de référence en unités SI, comme cela est exigé par l'IEC 60904-2. Les dispositifs de référence primaire, étalonnés conformément à ces procédures, servent à établir la traçabilité d'autres dispositifs PV de référence qui constituent alors des dispositifs de référence secondaire.

Comme cela est déjà mentionné à l'Article 1, les méthodes décrites dans la présente annexe sont limitées aux technologies PV à jonction unique. Par ailleurs, elles n'ont à ce jour été validées que pour la technologie au silicium cristallin, bien qu'elles puissent s'appliquer à d'autres technologies.

Les méthodes ont été mises en œuvre dans différents laboratoires dans le monde et validées par des intercomparaisons internationales, notamment le World Photovoltaic Scale (WPVS). Toutefois, la description donnée par le présent document est plus générale. Pour de plus amples informations sur les différentes mises en œuvre, les références des publications contrôlées par des pairs sont données à la fin de chaque procédure.

Les estimations de l'incertitude se fondent sur U_{95} (facteur d'élargissement k = 2) pour toutes les composantes individuelles. L'incertitude composée élargie est calculée comme étant la racine carrée de la somme des carrés de toutes les composantes. Les incertitudes données sont des expressions simplifiées (limitées aux composantes principales) telles que fournies par les laboratoires ayant mis la procédure en œuvre. Ces calculs d'incertitude servent uniquement de lignes directrices et doivent être adaptés à la mise en œuvre particulière de chaque procédure dans un laboratoire donné. Les incertitudes obtenues par la mise en œuvre de ces méthodes peuvent être très différentes. Les incertitudes estimées par un laboratoire donné doivent être fondées sur une analyse explicite spécifique et ne peuvent pas être prises par référence aux estimations de l'incertitude du présent document.

A.1.2 Exemples des méthodes validées

A.2 Méthode sous lumière solaire globale (GSM – *global sunlight method*)

A.3 Étalonnage par sensibilité spectrale différentielle (DSR – *differential spectral responsivity calibration*)

A.4 Méthode du simulateur solaire (SSM – *solar simulator method*)

A.5 Méthode de la lumière solaire directe (DSM – *direct sunlight method*)

A.1.3 Liste des symboles communs

I_{SC} courant de court-circuit du dispositif PV de référence

T_j température du dispositif PV de référence

M_G facteur de correction de l'éclairement énergétique (voir ci-dessous)

M_T facteur de correction de la température (voir ci-dessous)

T_{coef} coefficient de température α du courant de court-circuit (IEC 60891) normalisé au courant de court-circuit à 25 °C et exprimé en 1/ K

SMM spectral mismatch factor (facteur de désadaptation des réponses spectrales) (IEC 60904-7)

λ longueur d'onde

$s(\lambda)$ sensibilité spectrale du dispositif PV de référence en fonction de la longueur d'onde λ

$s(\lambda,T_j)$ sensibilité spectrale du dispositif PV de référence en fonction de la longueur d'onde λ et de la température T_j

$\frac{\partial s(\lambda,T_j)}{\partial T}$ dérivée partielle de la sensibilité spectrale selon la température en fonction de la longueur d'onde λ

$\tilde{s}(\lambda)$ sensibilité spectrale différentielle du dispositif PV de référence

$E_{meas}(\lambda)$ répartition spectrale de l'éclairement énergétique de la lumière solaire naturelle ou simulée

$E_{ref}(\lambda)$ répartition spectrale de l'éclairement énergétique de référence ou normalisé selon l'IEC 60904-3

G_{dir} éclairement énergétique direct

G_{dif} éclairement énergétique diffus dans le plan

G_T éclairement énergétique total dans le plan

G_{STC} éclairement énergétique aux conditions normales d'essai (= 1 000 Wm–2)

CV calibration value (valeur d'étalonnage), c'est-à-dire I_{SC} aux conditions normales d'essai

AM air mass (masse d'air) (masse atmosphérique)

STC standard test conditions (conditions normales d'essai) (1 000 Wm^{-2}, 25 °C et $E_{ref}(\lambda)$)

P pression atmosphérique locale

P_0 101 300 Pa

θ angle d'élévation du soleil

A.1.4 Formules communes

Les méthodes décrites dans les Articles A.2, A.4 et A.5 ont certains calculs en commun, détaillés en A.1.4. Les informations détaillées des différentes mises en œuvre sont ensuite décrites dans chaque paragraphe.

Le courant I_{SC} n'est généralement pas mesuré à exactement 1 000 Wm $^{-2}$, mais à un niveau d'éclairement énergétique proche. En prenant pour hypothèse que le courant I_{SC} du dispositif PV de référence varie linéairement avec l'éclairement énergétique selon l'IEC 60904-10, la correction suivante est faite:

$$I_{SC}\left(G_{STC}\right) = I_{SC} M_G = I_{SC}\frac{G_{STC}}{G_T} \tag{A.1}$$

Si le mesurage de l'éclairement énergétique est traçable par rapport à la WRR, alors le relevé de l'éclairement énergétique peut être corrigé pour la différence d'échelle en unités SI.

Les conditions normales d'essai (STC – *standard test conditions*) stipulent une température du dispositif de 25 °C, mais les mesurages ne sont pas toujours effectués à cette température. Il convient de prendre en compte les écarts de température dans le bilan de l'incertitude. Il est aussi possible de corriger le courant I_{SC} de la température de mesure T_j à la température de 25 °C, en le multipliant par le facteur de correction de la température M_T défini par:

$$I_{SC}(25\ ℃) = I_{SC}(T_j) M_T = \frac{I_{SC}(T_j)}{1 - T_{coef}(25\ ℃ - T_j)} \tag{A.2}$$

La correction de la différence entre la sensibilité spectrale du dispositif PV de référence à étalonner et celle du dispositif utilisé pour mesurer l'éclairement énergétique peut être calculée comme une désadaptation des réponses spectrales *SMM:*

$$SMM = \frac{\int_0^{\infty} E_{ref}(\lambda) d\lambda}{\int_0^{\infty} E_{meas}(\lambda) d\lambda} \frac{\int_0^{\infty} E_{meas}(\lambda) s(\lambda) d\lambda}{\int_0^{\infty} E_{ref}(\lambda) s(\lambda) d\lambda} \tag{A.3}$$

NOTE La Formule (A.3) est la même formule que celle présentée dans l'IEC 60904-7 dans le cas d'un détecteur thermopile dont la sensibilité spectrale du dispositif en essai est désormais la sensibilité spectrale du dispositif PV de référence à étalonner.

La plage d'intégration se situe au-dessus de toutes les longueurs d'onde. L'éclairement énergétique de $E_{ref}(\lambda)$ est zéro en dessous de 280 nm. C'est également le cas pour $E_{meas}(\lambda)$, en particulier sous la lumière solaire naturelle. Pour des raisons pratiques, l'intégrale explicite ne peut être calculée au-dessus de 4 000 nm, puisque $E_{ref}(\lambda)$ n'est pas définie explicitement, mais peut seulement être calculée comme l'intégrale de l'éclairement énergétique entre 4 000 nm et l'infini. $E_{meas}(\lambda)$ est généralement mesurée uniquement pour une plage de longueurs d'onde encore plus petite, par exemple allant jusqu'à 2 500 nm. Afin de calculer les intégrales, une approximation appropriée (troncature des intégrales) ou une extension des données de l'éclairement énergétique spectral mesuré par extrapolation ou modélisation peut être utilisée, mais doit être prise en compte dans le calcul de l'incertitude. Par exemple, la troncature des intégrales à 4 000 nm pour la DSM donne lieu à une erreur de 0,025 %, tandis que la troncature à 2 500 nm donne lieu à une erreur de 0,116 %. Ces valeurs ont été déterminées par l'éclairement énergétique spectral direct et global tel que défini dans l'IEC 60904-3.

Les radiomètres à cavité utilisés pour le mesurage de l'éclairement énergétique sont réputés détecter parfaitement l'éclairement énergétique à toutes les longueurs d'onde. Il convient de corriger ou de prendre en compte dans l'incertitude de mesure les écarts possibles par rapport à cette caractéristique parfaite.

La valeur d'étalonnage (CV) du dispositif PV de référence est alors calculée comme étant:

$$CV = I_{SC} \frac{M_G M_T}{SMM} \tag{A.4}$$

A.1.5 Documents de référence

– IEC 60891: *Dispositifs photovoltaïques – Procédures pour les corrections en fonction de la température et de l'éclairement à appliquer aux caractéristiques I-V mesurées*

– IEC 60904-7: *Dispositifs photovoltaïques – Partie 7: Calcul de la correction de désadaptation des réponses spectrales dans les mesures de dispositifs photovoltaïques*

– IEC 60904-10: *Dispositifs photovoltaïques – Partie 10: Méthodes de mesure de la linéarité*

– C. R. Osterwald et al., «The results of the PEP'93 intercomparison of reference cell calibrations and newer technology performance measurements: Final Report», *NREL/TP-520-23477,* 1998, 209 pages

– C. R. Osterwald et al., «The world photovoltaic scale: an international reference cell calibration program», *Progress in Photovoltaics,* **7**, 1999, 287-297

– K. Emery, «The results of the First World Photovoltaic Scale Recalibration», *NREL/TP-520-27942,* 2000, 14 pages