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

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

PHOTOVOLTAIC DEVICES –

**Part 4: ~~Reference solar~~ 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- withdrawn,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: ~~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

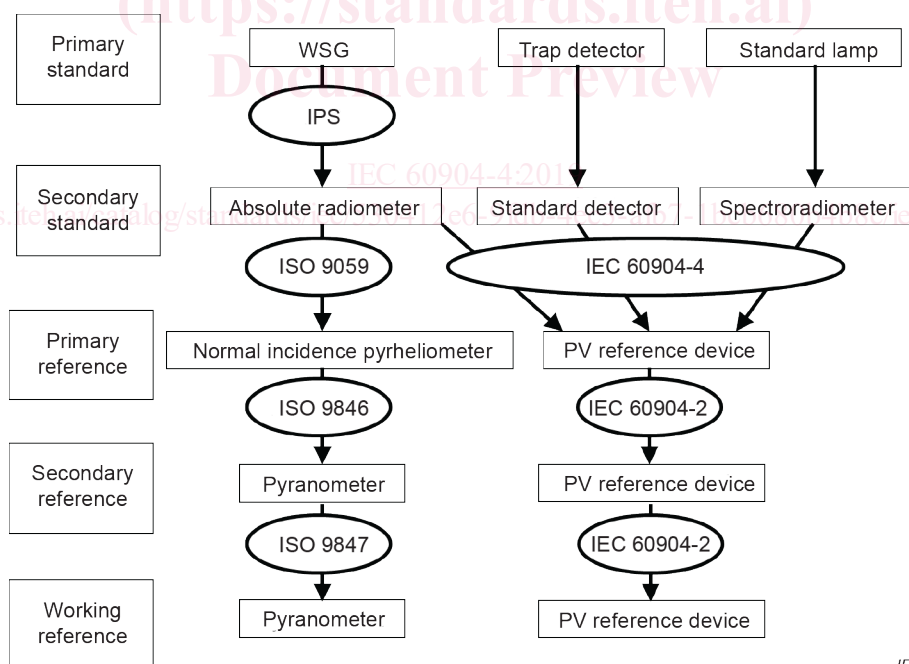
The WRR has been compared several times to the SI radiometric scale. While in previous comparisons the two scales were found to be indistinguishable within the uncertainty of the comparison, the latest comparison of scales established that there is a systematic shift between the scales, with WRR reading 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.



IEC

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.

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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 $1/^\circ\text{C K}$
MMF	mismatch factor (see below)
<i>SMM</i>	spectral mismatch factor (IEC 60904-7)
λ	wavelength
$S(\lambda)$	spectral response of reference cell