BS EN 60904-4:2009

Photovoltaic devices —

Part 4: Reference solar devices — Procedures for establishing calibration traceability

National foreword

This British Standard is the UK implementation of EN 60904-4:2009. It is identical to IEC 60904-4:2009.

The UK participation in its preparation was entrusted to Technical Committee GEL/82, Solar photovoltaic energy systems.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Compliance with a British Standard cannot confer immunity from legal obligations.

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Dispositifs photovoltaïques -
Partie 4: Dispositifs solaires de référence -
Procédures pour établir
la traçabilité de l'étalonnage
(CEI 60904-4:2009)

Photovoltaische Einrichtungen -
Teil 4: Referenz-Solarelemente -
Verfahren zur Feststellung
der Rückverfolgbarkeit der Kalibrierung
(IEC 60904-4:2009)

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Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Central Secretariat: Avenue Marnix 17, B - 1000 Brussels

Foreword

The text of document 82/533/CDV, future edition 1 of IEC 60904-4, prepared by IEC TC 82, Solar photovoltaic energy systems, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60904-4 on 2009-09-01.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2010-06-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2012-09-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60904-4:2009 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60891	NOTE Harmonized as EN 60891:1994 (not modified).
IEC 60904-1	NOTE Harmonized as EN 60904-1:2006 (not modified).
IEC 60904-3	NOTE Harmonized as EN 60904-3:2008 (not modified).
IEC 60904-7	NOTE Harmonized as EN 60904-7:2009 (not modified).
IEC 60904-8	NOTE Harmonized as EN 60904-8:1998 (not modified).
IEC 60904-9	NOTE Harmonized as EN 60904-9:2007 (not modified).
IEC 61836	NOTE Harmonized as CLC/TS 61836:2009 (not modified).

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application 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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60904-2	-[1]	Photovoltaic devices - Part 2: Requirements for reference solar devices	EN 60904-2	2007[2]
ISO/IEC 17025	-[1]	General requirements for the competence of testing and calibration laboratories	EN ISO/IEC 17025	2005[2]
ISO/IEC Guide 98-3	2008	Uncertainty of measurement - Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)	-	-
ISO 9059	-[1]	Solar energy - Calibration of field pyrheliometers by comparison to a reference pyrheliometer	-	-
ISO 9846	-[1]	Solar energy - Calibration of a pyranometer using a pyrheliometer	-	-

[1] Undated reference.

[2] Valid edition at date of issue.

CONTENTS

PHOTOVOLTAIC DEVICES –

Part 4: Reference solar 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 reference solar devices to SI units as required by IEC 60904-2.

This standard 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 IEC 60904-1 and IEC 60904-3.

This standard has been written with single junction PV reference solar devices in mind, in particular crystalline Silicon. 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 referenced documents are indispensable for the application 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 60904-2, *Photovoltaic devices – Part 2: Requirements for reference solar devices*

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 following terms and definitions 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.

3.1
primary standard
a device, which implements physically one of the SI units or directly related quantities. They are usually maintained by national metrology institutes (NMIs) or similar organisations 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

and repeatability of measurement of the quantity it represents are guaranteed to the maximum extent possible by current technology.

NOTE 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
a 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. It does not necessarily use the same technical principles as the primary standard, but strives to achieve similar long-term stability, precision and repeatability.

NOTE 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.

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. Often primary references can be realised at much lower costs than secondary standards.

NOTE Typically a solar cell is used as a reference solar device for the measurement of natural or simulated solar irradiance.

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

NOTE The most common secondary references for the measurement of natural or simulated solar irradiance are solar cells and solar modules.

3.5
traceability
the 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.

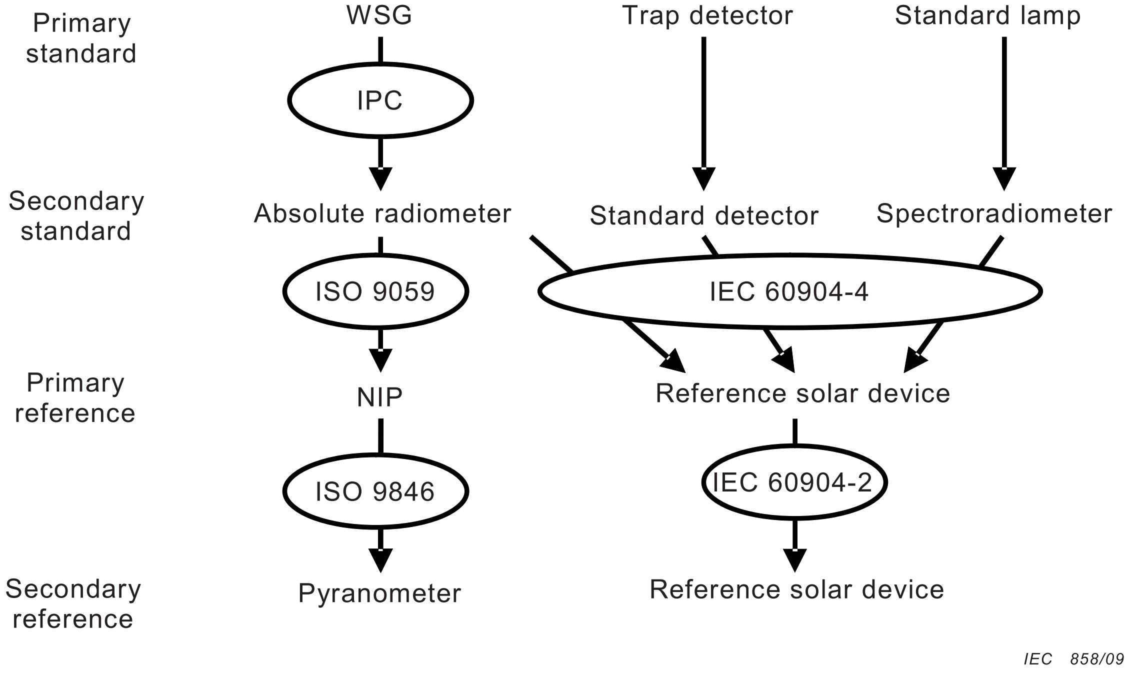
NOTE The WRR has been compared twice to the SI radiometric scale and shown to be within their mutual uncertainty levels. Therefore traceability to WRR automatically provides traceability to SI units. However, the uncertainty of the ratio WRR/SI units needs to be taken into account. The World Radiation 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

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 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 device (IEC 60904-2 and IEC 60904-4)
Secondary reference	Quartz watch	Pyranometer (ISO 9846) Reference solar 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 (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, 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 constituting a primary reference.

NOTE 2 The transfer from one 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) 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.

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 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) authorising the report;

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

7 Marking

The calibrated 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).

Annex A
(informative)

Examples of validated calibration procedures

A.1 General

This annex describes examples of calibration procedures for PV reference solar cells as primary reference devices, together with their stated uncertainties. These procedures serve to establish the traceability of 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.

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 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 standard is more generalised. 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 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 have to be based on an explicit analysis and cannot be taken by reference to the uncertainty estimates in this standard.

A.1.1 Examples of validated methods

A.2 Global sunlight method
A.3 Differential spectral responsivity calibration
A.4 Solar simulator method
A.5 Direct sunlight method

A.1.2 List of common symbols

I_{SC}	short circuit current of reference cell
T_j	temperature of reference cell
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
MMF	mismatch factor (see below)
λ	wavelength
$S(\lambda)$	spectral response of reference cell
$s(\lambda)$	differential spectral responsivity of reference cell
$E_m(\lambda)$	spectral irradiance distribution of natural or simulated sunlight
$E_s(\lambda)$	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} 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 W/m^2, 25 °C and $E_s(\lambda)$)
P local air pressure
P_0 101 300 Pa
θ solar elevation angle

A.1.3 Common equations

The methods described in Clauses A.2, A.4 and A.5 have some common calculations, which are detailed in this subclause. 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:

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

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

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

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

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

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

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

A.1.4 References documents

– 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

The establishment of traceability is based on the calibration using the Continuous Sun-and-Shade Method as described in ISO 9846. The reference solar cell 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 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 compared at 5-year intervals with the World Standard Group (WSG) establishing the World Radiometric Reference (WRR). The calibration factor for the photovoltaic reference cell is determined from the measured short circuit current, scaled to 1 000 W/m^2 and corrected for spectral mismatch (IEC 60904-7) based on the measured spectral irradiance of the global sunlight and the relative spectral response of the reference solar cell to be calibrated.

Under certain conditions the simplified global sunlight method is applicable. The short-circuit current of the reference cell is scaled to 1 000 W/m^2 and then plotted versus pressure corrected geometric air mass. The calibration value is determined from a linear least square fit at air mass 1,5. A spectral mismatch correction is not required and hence the measurements of the spectral irradiance of the sunlight and the spectral response are not necessary. In the simplified version of the global sunlight method no explicit spectral mismatch correction is performed and it 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 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 over a broad range of the solar spectrum e.g. crystalline silicon devices. Significant errors may be introduced for narrow spectral response devices.

A.2.1 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 WRR.

c) A pyranometer, traceable to 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 reference device under test capable of maintaining the cell temperature at (25 ± 2)°C throughout all calibration runs.

f) Traceable means to measure the short circuit current of the solar cell 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) 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) Apparatus to determine the relative spectral response of the reference solar cell.

NOTE 2 Not required in simplified version.

j) Means to measure the sun's elevation to a precision of ±2°. Alternatively, the elevation of the sun during the data sampling can be taken from almanacs or computed, as long as the precision 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) 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.2.2 Measurements

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

a) Determine the relative spectral response of the reference cell to be calibrated.

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 degrees at P_0).

c) Mount the cavity radiometer on the sun-pointing device (item A.2.1.a). Available radiometers have their own electronic unit which shall be connected to the instrument following the manufacturer's recommendations. Allow sufficient time to stabilise the electronic unit.

d) Mount the reference solar cell to be calibrated coplanar on the mounting platform, attaching it to the mounting block and maintain the cell temperature at (25 ± 2) °C.

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) 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 reference solar cell 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 reference solar cell to be calibrated

   6) Record $E(\lambda)$, the spectral irradiance of the global natural sunlight.

NOTE 3 Not required in simplified version.

   7) 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) Record P, the local air pressure.

NOTE 5 Only required in simplified version.

   9) Repeat Steps 1 to 6 several times.

NOTE 6 Not required in simplified version.

10) 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 below AM 1,5 to above 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.2.3 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 reference solar cell to be calibrated to 1000 W/m^2 according to Equation A.1.

d) Correct for temperature according to Equation A.2.

NOTE 1 This is normally not required as the temperature is maintained as described in A.2.2.d) and the allowed temperature deviation is accounted for in the uncertainty budget.

e) Correct for spectral mismatch according to Equation A.3, where $E_m(\lambda)$ is the measured spectral irradiance of the global natural sunlight.

f) Calculate the calibration value according to Equation 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 reference device:

$$CV = (CV_1 + CV_2 + \ldots + CV_n) / n. \quad \text{(A.5)}$$

j) In the simplified version the 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/m^2.

NOTE 2 This 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:

$$AM = P / (P0 \times \sin(\theta)) \quad \text{(A.6)}$$

   3) Reject all data samples where AM is larger than 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, 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 smaller the uncertainty of the procedure, the more data points in the least-squares fit are close to AM 1,5.

NOTE 4 It is permissible to use only data from half a day. 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 reference device by the formula:

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

7) Perform steps h) and i).

A.2.4 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 % 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 %**

A.2.5 References documents

– 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 calibration)

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 reference cell 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 concerning linearity or spectral match.

A.3.1 Equipment

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

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

b) lamp(s) with lens or mirror entrance optics (recommended are quartz-halogen lamp to cover wavelengths above 400 nm; and Xenon-arc lamps for wavelengths below 400 nm);

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;

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

f) standard radiation detector(s) with temperature control directly traceable to SI units. These detectors shall be of photodiodes with the best available linearity, uniformity and stability;

g) adjustable aperture (imaged onto the reference cell);

h) means for maintaining the temperature of the reference cell at (25 ± 2)°C;

i) means for measuring the AC short-circuit currents of the reference cell, the standard detector(s) and the monitoring detector, e.g. 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 is used for the reference cell and the standard detector;

j) means for measuring the DC component of the reference cell I_b as defined in step A.3.2.f.

A.3.2 Test procedure

a) Set and maintain the temperature of the reference cell to (25 ± 2) °C.

b) Adjust the aperture until its image coincides with the active area of the reference cell within ± 1 mm.

c) Mount the standard detector in a position close to the focus of the monochromatic beam collecting the whole radiation power.

d) Calibrate the monochromatic irradiance source of A.3.1.a. (without bias radiation) with respect to its relative spectral irradiance.

e) Use its chopped monochromatic beam to determine the ratio of the AC short-circuit currents of the monitor photodiode ($\Delta I_{mon.cal}$) and standard detector (ΔI_{st}) measured simultaneously at wavelength intervals of not more than 10 nm over the whole responsivity range.

f) Set the white bias irradiance E_b to the desired operational level (between 10 Wm^{-2} and 1 100 Wm^{-2}) and measure the corresponding DC short circuit current $I_b = I_{sc}(E_b)$.

g) Measure the relative spectral responsivity of the reference cell by using the chopped monochromatic radiation of irradiance source A.3.1.a) and determining the ratio of the short-circuit currents of reference cell (ΔI_{ref}) and monitor photodiode (ΔI_{mon}) and calculate the relative differential spectral responsivity $s(\lambda,I_b)_{rel}$ of the reference cell under bias irradiance E_b:

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

where $S_{st}(\lambda)$ = spectral responsivity of the standard detector at wavelength λ.

h) Repeat steps f) and g) at 5 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 responsivity.

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).

j) The absolute differential spectral responsivity $s(\lambda_i,I_o)$ 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.

A.3.3 Data analysis

a) Calculate the ratio $k_l(\lambda_i)$ = (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_o 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):

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

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

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

with

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

and

$$I_b = I_{sc}(E_b) \quad \text{(A.12)}$$

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:

$$CV = s_{AM1.5} E_{STC} \quad \text{(A.13)}$$

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

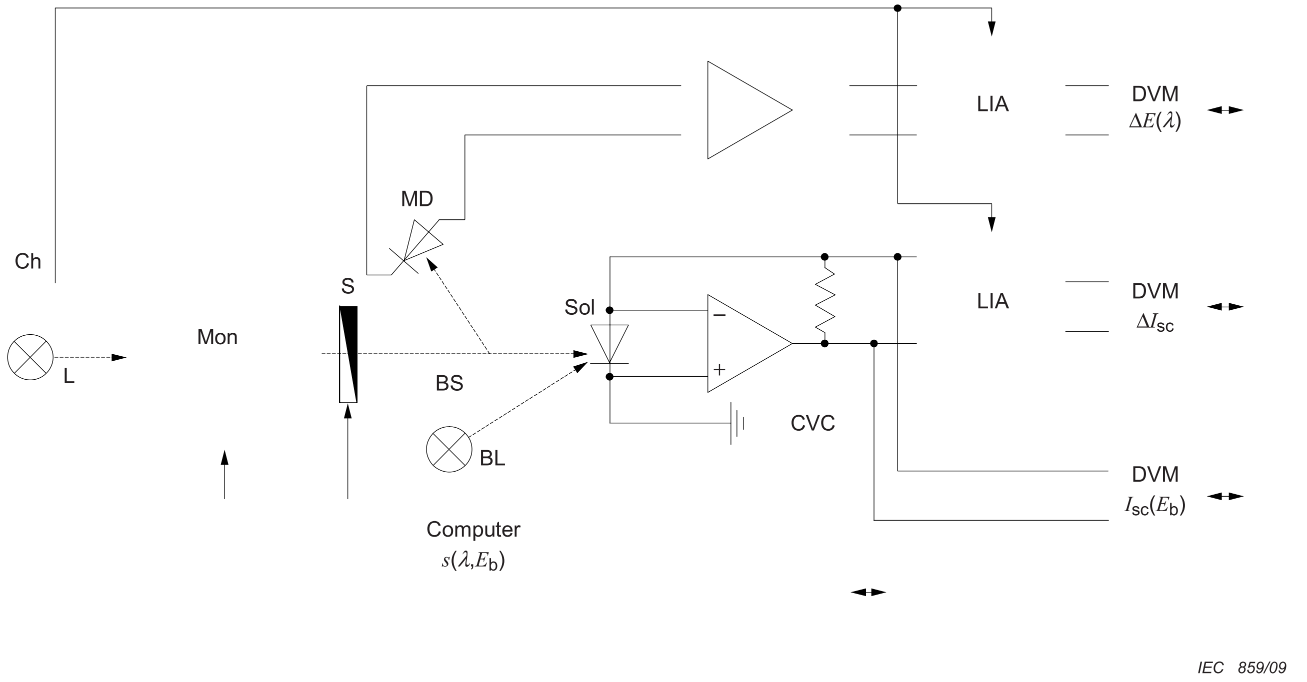
A.3.4 Uncertainty estimate

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

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 metrology institutes (NMIs).

Table A.2 – Typical uncertainty components (k = 2) of a differential spectral responsivity calibration

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 %**



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 and standard detector respectively, CVC: current-voltage converter, LIA: lock-in amplifier

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

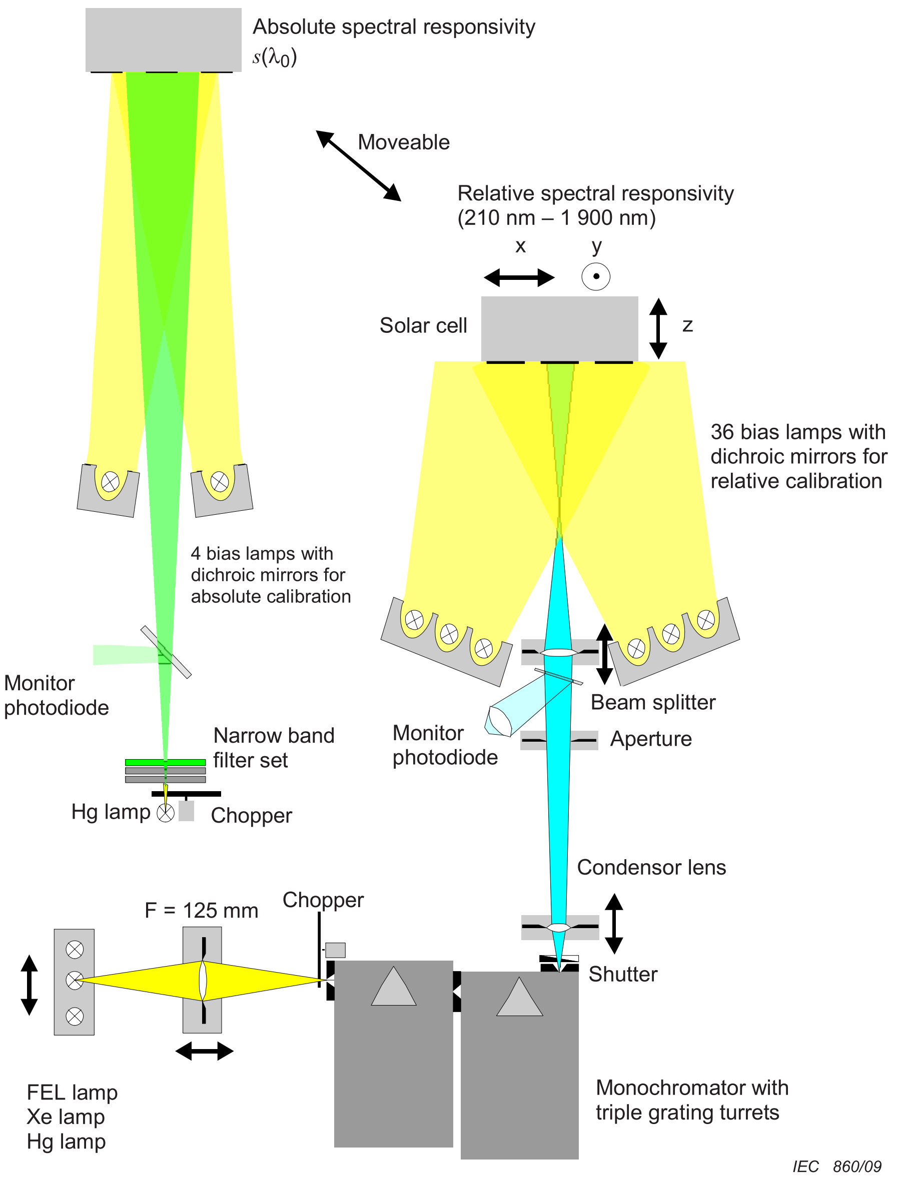


Figure A.2 – Optical arrangement of differential spectral responsivity calibration

A.3.5 References documents

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– J. Metzdorf, S. Winter, T. Wittchen "Radiometry in photovoltaics: calibration of reference solar cells and evaluation of reference values" *metrologia* **37** (2000) 573-578.

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A.4 Solar simulator method

Traceability is based on the absolute spectral irradiance of simulated sunlight and relative spectral responsivity of the reference solar cell 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 WRR. The calibration value is computed from the measured spectral responsivity of the reference cell, the spectral irradiance distribution of the solar simulator and the reference solar spectral irradiance distribution (IEC 60904-3).

A.4.1 Equipment

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

a) A solar simulator of class AAA as defined in IEC 60904-9.

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

c) Means for measuring spectral responsivity of the reference cell 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 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 reference cell which shall comply with the general measurement requirements of IEC 60904-1.

g) Means for maintaining the temperature of the reference cell at (25 ± 2)°C.

A.4.2 Calibration procedure

a) The relative spectral response of the reference cell 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}, using a thermal photo detector such as thermopile.

c) The absolute spectral irradiance distribution in the test plane shall be measured by the calibrated spectroradiometer as described in CIE 63-1984.

NOTE For the calculation as described in A.4.3 a) the wavelength range has to span at least the same interval as $S(\lambda)$. 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 reference cell shall be located in the test plane of the simulator. The cell temperature shall be maintained at (25 ± 2)°C. The short-circuit current of the cell is to be measured more than 10 times and the mean value is to be calculated.

A.4.3 Data analysis

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

$$CV = I_{SC} \frac{\int E_{s}(\lambda) S(\lambda)\, d\lambda}{\int E_{m}(\lambda) S(\lambda)\, d\lambda} \qquad \text{(A.14)}$$

where:

$E_{m}(\lambda)$ 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 WRR, as described in A.4.1.e). The calibration value (CV) is computed according to Equation A.4 where G_{T} is the total irradiance of the solar simulator measured by a cavity radiometer traceable to WRR.

c) Repeating the steps in A.4.2. and A.4.3. twice, the mean CV is to be calculated as the final calibration value.

A.4.4 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 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:	< 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 vs SI units	< 0,4 %
Uncertainty of irradiance measurement	< 0,2 %
Uncertainty due to unstable cell temperature:	< 0,2 %
Uncertainties due to spectral irradiance deviations between test conditions and the reference spectral irradiance of AM 1,5 (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 and cavity radiometer:	< 0,2 %
Combined expanded uncertainty	**0,6 %**

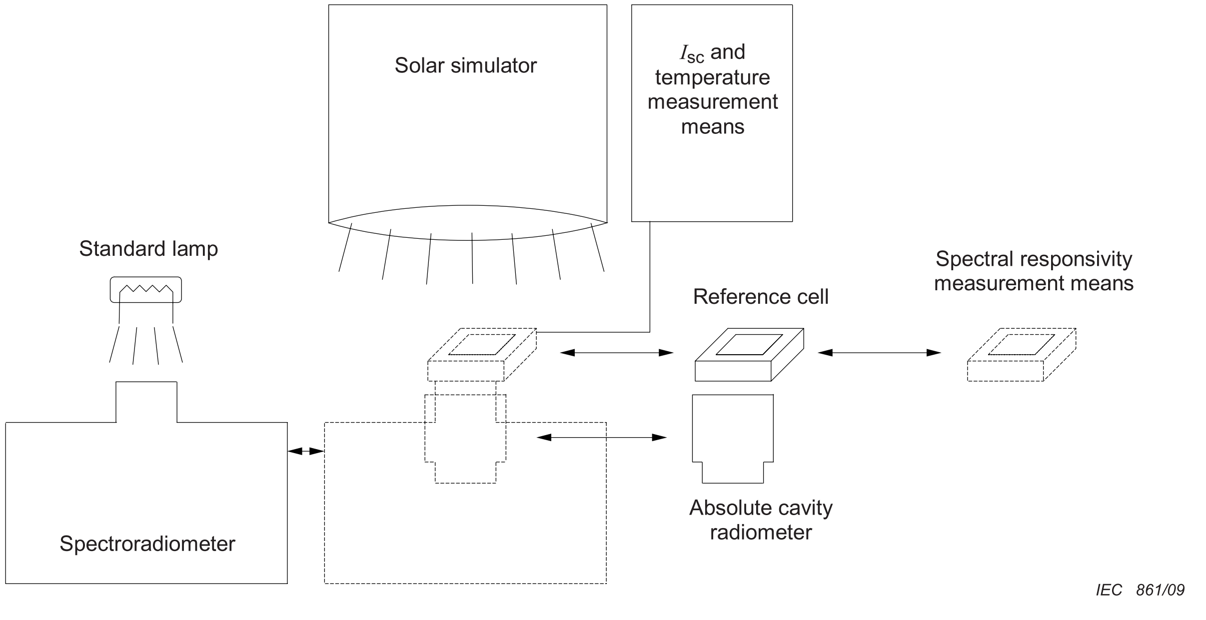

Figure A.3 – Schematic apparatus of the solar simulator method

A.4.5 References documents

– 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.

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– CIE 53-1982 "Methods of Characterizing the Performance of radiometers and Photometers", ISBN 92 9034 053 3.
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A.5 Direct sunlight method

The reference solar cell 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 is measured, scaled to 1 000 W/m^2 and corrected for temperature and spectral mismatch between the direct beam natural sunlight spectrum as measured by a spectoradiometer and the defined standard spectrum (IEC 60904-3). The relative spectral response of the solar cell has also to be determined.

A.5.1 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 WRR.
c) A collimator tube for the solar cell having the same viewing angle as the cavity radiometer.
d) A temperature controlled mounting block for the reference cell to be calibrated capable of maintaining the junction temperature at (25 ± 2) °C throughout all calibration runs. Means to measure the temperature of the reference solar cell to be calibrated.
e) Traceable means to measure the short circuit current of the solar cell 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 of the solar cell.

A.5.2 Measurements

a) Mount the reference cell 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, $E_m(\lambda)$, 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 reference solar cell to be calibrated.
    3) Measure the reference cell temperature, T_j.
    4) Repeat these steps at least four times. These repetitions shall be distributed in time during the spectral irradiance measurement.
c) Perform a minimum of five replications of step b) on at least three separate days.

A.5.3 Data analysis

a) Perform the correction of Equation 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.

e) Average the calibration values for each day and calculate the arithmetic average CV using Equation A.5.

f) Reject any points that meet the following criteria

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

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

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

g) Verify that at least 3 days data with a minimum of 5 sets per day of valid data exist. If not take additional measurements until this criterion is met.

A.5.4 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 %.

Table A.5 – Typical uncertainty components (k = 2) of a direct sunlight method

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 %**

A.5.5 References documents

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– ASTM E 1125 “Standard test method for calibration of primary non-concentrator terrestrial photovoltaic reference cells using a tabular spectrum”.

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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*

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