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Introduction

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Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



DRAFT International Standard

ISO/DIS 20256

Space systems — Solar cells — Calibration procedures

ICS: 49.140

ISO/TC 20/SC 14

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Foreword

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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document is consistent with the principles associated with photovoltaic solar cells established by IEC/TC 82, *Solar photovoltaic energy systems*. It provides specific requirements and procedures that apply to the generation of primary and secondary reference solar cells used for solar cell calibration for space applications. Wherever possible the document refers to existing standards such as the IEC 60891 and the IEC 60904 series which cover all aspects of solar cell calibration and measurements for terrestrial applications.

This document focusses on the requirements and procedures for the calibration of primary and secondary reference solar cells under the air mass zero (AM0) spectrum being applicable to both single-junction and multi-junction solar cells. The primary calibration methods given in the Annex serve as examples of acceptable calibration techniques.

Space systems — Solar cells — Calibration procedures

1 Scope

This document specifies the requirements for primary and secondary calibration procedures of single-junction and multi-junction space solar cells. The main body of this document specifies the requirements for Air Mass Zero (AM0) standard primary and secondary calibration.

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 60891, *Photovoltaic devices — Procedures for temperature and irradiance corrections to measured I-V characteristics*

IEC 60904-1, *Measurement of photovoltaic current-voltage characteristics*

IEC 60904-1-1, *Measurement of current-voltage characteristics of multi-junction photovoltaic (PV) devices*

IEC 60904-2, *Requirements for photovoltaic reference devices*

IEC 60904-4, *Reference solar devices — Procedures for establishing calibration traceability*

IEC 60904-5, *Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method*

IEC 60904-7, *Computation of the spectral mismatch correction for measurements of photovoltaic devices*

IEC 60904-8, *Measurement of spectral responsivity of a photovoltaic (PV) device*

IEC 60904-8-1, *Measurement of spectral responsivity of multi-junction photovoltaic (PV) devices*

IEC 60904-9, *Solar simulator performance requirements*

IEC 60904-10, *Methods of linearity measurement*

IEC 60050, *International electrotechnical vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60904-4, 60904-10, 60904-7, and the following apply.

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

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

3.1**absolute cavity radiometer**

highly precise instrument used to measure solar irradiance

Note 1 to entry: A combined electrical substitution and cavity radiometer where the electrical substitution inequivalence, efficiency of the cavity, the area of the entrance aperture, radiative and conductive losses, and other energy exchanges are accounted for such that the electrically substituted heating can be absolutely equated to the radiant heating of the detector

Note 2 to entry: Most currently existing absolute cavity radiometers are designed for the measurement of direct solar irradiance. The World Radiation Reference (WRR) scale for solar irradiance observations used in many meteorological and climatological applications is defined by a group of well-characterized absolute cavity radiometers maintained by the World Radiation Center (WRC) in Davos, Switzerland.

3.2**air mass****AM**

length of path through the earth's atmosphere traversed by the direct solar beam, expressed as a multiple of the path traversed to a point at sea level with the sun directly overhead

Note 1 to entry: The value of air mass is 1 at sea level with a cloudless sky when the sun is directly overhead and the air pressure $P = 1,013 \times 10^5$ Pa.

At any point on the earth surface, the value of the air mass is given by:

$$AM = (P / P_0) \times (1/\sin\theta) \quad (1)$$

where

P is the local air pressure in pascal;

P_0 is $1,013 \times 10^5$, in pascal;

θ is the solar elevation angle (degrees)

3.3**air mass zero****AM0**

absence of atmospheric attenuation of the solar irradiance at one astronomical unit from the sun

3.4**AM0 standard solar cell**

calibrated solar cell used to measure irradiance or to set simulator irradiance levels in terms of an air mass zero (AM0) reference solar spectral irradiance distribution

3.5**ambient temperature** **T_{amb}**

temperature of the air surrounding the solar cell as measured in a vented enclosure and shielded from solar, sky and ground radiation

3.6**angle of incidence**

angle between the direct irradiant beam and the normal to the active surface

3.7**astronomical unit****AU**

unit of length approximately equal to the mean distance between the Sun and the Earth with a currently accepted value of $(149\,597\,870\,691 \pm 3)$ m^[1]

3.8 junction temperature

T_j

temperature of p-n junction in a solar cell that affects the performance, efficiency, and lifetime

Note 1 to entry: In the absence of light, cell and junction temperature are equivalent. In case of illumination, the junction temperature cannot be directly measured.

[SOURCE: IEC 60904-5:2022, Introduction]

Note 2 to entry: T_j can be derived from applying the methods described in IEC 60904-5.

3.9 component solar cell

specially manufactured solar cell, with only one active junction and the same spectral responsivity as one sub cell of a multi-junction solar cell

3.10 conversion efficiency

ratio of “maximum electrical power output” to the product of generator area and incident irradiance measured under defined test conditions and expressed as a percentage

3.11 current-voltage characteristics

output current of a solar cell as a function of output voltage, at a particular temperature and irradiance

Note 1 to entry: $I = f(V)$.

3.12 device temperature

T_d

temperature of a solar cell read off from a temperature sensor fixed to the solar cell

Note 1 to entry: This temperature is typically different from the cell or junction temperature as soon as the solar cell is being illuminated

Note 2 to entry: Reference devices often are equipped with temperature sensors fixed to them. In general, there will be an offset between the device temperature and the cell temperature which can be determined using the methods described in IEC 60904-5. When the device temperature of the reference device during calibration and application is set to the same value no corrections are needed. One only has to keep in mind that nominally identical cells (in terms of spectral responsivity) will then have slightly different spectral responsivities when they are not adjusted to the same cell temperature T_j . This adds to the mismatch factor.

3.13 fill factor

FF

ratio of maximum electrical power to the product of open circuit voltage and short-circuit current

Note 1 to entry: $FF = P_{\max}/(V_{oc} \times I_{sc})$

3.14 irradiance

E_e

density of incident radiant flux with respect to area at a point on a real or imaginary surface, expressed by

$$E_e = d\Phi_e/dA$$

where Φ_e is radiant flux and A is area on which the radiant flux is incident

Note 1 to entry: It is expressed in W/m^2 [2].

3.15**irradiation**

exposure of a substance to energetic particles that penetrate the material and have the potential to transfer energy to the material^[3]

3.16**linearity**

property that two physical quantities or properties vary linearly

EXAMPLE With respect to a solar cell, relation of short-circuit current with irradiance shows linearity.

3.17**maximum power**

$P_{\max}$

power at the point on the current-voltage characteristics where the product of current and voltage is a maximum at a particular temperature and irradiance

Note 1 to entry: $P_{\max} = V_{\max} \times I_{\max}$

3.18**maximum power current**

$I_{\max}$

current corresponding to maximum power at a particular temperature and irradiance

3.19**maximum power voltage**

$V_{\max}$

voltage corresponding to maximum power at a particular temperature and irradiance

3.20**multi-junction solar cell**

photovoltaic cell that consists of multi p-n junctions made of different semiconductor materials to absorb different portions of the solar spectrum, thereby improving the efficiency of the solar cell compared to single-junction cell

Note 1 to entry: Each layer in a multi-junction solar cell is tuned to capture a specific range of wavelengths, allowing for the conversion of more sunlight into electrical energy.

3.21**open circuit voltage**

V_{oc}

<of a PV reference device> voltage generated by a solar cell without electrical loading at a particular temperature and irradiance

3.22**ozone content**

volume of ozone at standard temperature and pressure in a vertical column of the atmosphere

Note 1 to entry: Ozone content is measured with a Dobson or a Brewer spectrophotometer.

3.23**primary reference solar cell**

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 realised at much lower costs than secondary standards.

Note 2 to entry: Typically, a solar cell is used as a reference solar device for the measurement of natural or simulated solar irradiance. In the context of this document the term “primary reference solar cell” is used (instead of primary reference).

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

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.

In the context of this document the sun is defined as an artefact by convention and thus can be considered as a primary standard itself. The sun is considered stable, i.e. it shall be assumed that there are no variations of its irradiance in time. Nevertheless, whenever calculations or corrections are made that make use of the AM0 spectrum tabulated in [Annex B](#) the related uncertainties of the AM0 reference spectrum and the total solar irradiance (TSI) value shall be taken into account in the uncertainty budget.

3.25**pyranometer**

radiometer normally used to measure global sunlight irradiance on a horizontal plane

Note 1 to entry: A pyranometer can also be used at an angle to measure the total sunlight irradiance on an inclined plane, which in this case includes an element caused by radiation reflected from the foreground.

3.26**pyrheliometer**

radiometer, complete with a collimator, used to measure direct sunlight irradiance

Note 1 to entry: This instrument is sometimes called normal incidence pyrheliometer, or NIP.

3.27**relative spectral responsivity**

$s(\lambda)_{\text{rel}}$

spectral responsivity normalized to a specified reference value, s_m

$$s(\lambda)_{\text{rel}} = s(\lambda) / s_m \quad (2)$$

Note 1 to entry: The specified reference value, s_m , can be an average value, a maximum value or an arbitrarily chosen value of $s(\lambda)$.

3.28**secondary reference solar cell**

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.

[SOURCE: IEC 60904-4:2019, 3.4]

3.29**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: It 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.

[SOURCE: IEC 60904-4:2019,3.2]

3.30

short circuit current

I_{sc}

output current of a solar cell in the short-circuit condition at a particular temperature and irradiance

3.31

single-junction solar cell

photovoltaic cell that consists of a single p-n junction to convert sunlight into electrical energy

Note 1 to entry: The efficiency of a single-junction solar cell is limited by the bandgap of the semiconductor material used, which determines the range of the solar spectrum it can absorb and convert into electricity.

3.32

solar cell

basic photovoltaic semiconductor device that converts sunlight directly into electrical energy, and that is the fundamental building block of solar panels

3.33

solar elevation angle

θ

angle between the direct solar beam and the horizontal plane

Note 1 to entry: This angle is measured in radians.

3.34

spectral irradiance

E(λ)

irradiance per unit wavelength

Note 1 to entry: The units are expressed as $\text{W}\cdot\text{m}^{-2}\cdot(\text{nm})^{-1}$.

3.35

spectral match of solar cells

matching of relative spectral responsivity of two solar cells

3.36

spectral photon irradiance

E_p(λ)

photon flux density at a particular wavelength

Note 1 to entry: $E_p(\lambda) = 5,034 \times 10^{15} \cdot \lambda \cdot E(\lambda)$, where λ is given in nanometers. The units of $E_p(\lambda)$ are expressed as $\text{s}^{-1}\cdot\text{m}^{-2}$.

3.37

spectral responsivity

s(λ)

short-circuit current (density) generated by unit irradiance at a particular wavelength as a function of wavelength

Note 1 to entry: For the spectral power responsivity which refers to the short-circuit current density generated by unit irradiance the unit is $\text{A}\cdot\text{W}^{-1}$. For the spectral irradiance responsivity which refers to the short-circuit current generated by unit irradiance, the unit is $\text{A}\cdot\text{W}^{-1}\cdot\text{m}^2$.

3.38

standard test conditions

STC

test conditions at cell temperature of 25 °C under AM0 solar spectral irradiance

3.39

sub cell

individual solar cell junction in a multi-junction solar cell

3.40

temperature coefficient of open circuit voltage

β

change of the open circuit voltage of a solar cell as a function of the change of cell temperature

Note 1 to entry: β is expressed in volts per degree Celsius (V/K).

3.41

temperature coefficient of short-circuit current

α

change of the short-circuit current of a solar cell as a function of the change of cell temperature

Note 1 to entry: α is expressed in amperes per Kelvin (A/K).

3.42

Total Solar Irradiance

solar constant

TSI

mean level of solar radiation that falls on a unit area normal to the line from the Sun per unit time outside the Earth's atmosphere at one astronomical unit

Note 1 to entry: The value and one-sigma uncertainty are presently taken to be $1\,361,1 \text{ W}\cdot\text{m}^{-2} \pm 0,5 \text{ W}\cdot\text{m}^{-2}$ ^{[4],[5]}.

3.43

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 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 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 standard. 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: IEC 60904-4:2019,3.6]

3.44

working reference solar cell

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

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.

[SOURCE: IEC 60904-4:2019,3.5]

4 Symbols and abbreviated terms

AM	air mass
AM0	air mass zero
AU	astronomical unit
α	temperature coefficient of short circuit current
β	temperature coefficient of open circuit voltage
CNES	Centre national d'études spatiales (French Space Agency)
EQE	External quantum efficiency
ESA	European Space Agency
$E(\lambda)$	spectral irradiance
$E_p(\lambda)$	photonic spectral irradiance
FF	fill factor
GMT	Greenwich mean time
GPS	global positioning system
$I_{\max}$	maximum power current
I_{sc}	short circuit current
I - V	current-voltage
JPL	Jet Propulsion Laboratory
NASA-GRC	National Aeronautics and Space Administration – Glenn Research Center
NIP	normal incidence pyrhelimeter
$P_{\max}$	maximum power
PTB	Physikalisch-Technische Bundesanstalt
PV	photovoltaic
$s(\lambda)$	spectral responsivity
$s(\lambda)_{\text{rel}}$	relative spectral responsivity
SI unit	Système international d'unités (International System of units)
STC	standard test conditions
T_{amb}	ambient temperature
T_d	device temperature
T_j	cell temperature
TM	telemetry

TSI	total solar irradiance
θ	solar elevation angle
V_{oc}	open circuit voltage
V_{max}	maximum power voltage
WRR	World Radiometric Reference
WSG	World Standard Group

5 General requirements and procedures for AM0 primary reference solar cells

5.1 General

This clause gives requirements for the classification, selection, packaging, marking, calibration and care of air mass zero (AM0) primary reference solar cells. Thereby, this chapter closely adheres to the philosophy described in IEC 60904-2 and IEC 60904-4 which are fully applicable with the amendments provided in the following.

5.2 Classification

Reference solar cells are specially calibrated devices which are typically used to set sun simulators to AM0 equivalent irradiance conditions in order to measure the performance of other solar cell devices under AM0 conditions. In this standard two different types of AM0 primary reference devices are distinguished, single-junction primary reference solar cells and multi-junction primary reference solar cells.

Traceable (synthetic) calibration procedures are necessary to transfer calibration from a standard or reference measuring (solar) irradiance (such as cavity radiometer, pyrhelimeter and pyranometer or a reference photodiode traceable to SI) to a PV reference solar device. The requirements for such procedures are outlined in IEC 60904-4. In addition, a direct measurement under quasi extraterrestrial illumination conditions is defined as a possible (high altitude) calibration procedure.

5.2.1 Single-junction AM0 primary reference solar cell

A reference device with only one junction being electrically active.

NOTE This includes also component cells which are representative of a subcell in a multi-junction solar cell. It has to be noted that component cells (unless being the top component cell) might show an unwanted sensitivity in a wavelength range in which the photons are absorbed by an upper electrically inactive layer (cp. [Figure 1](#)^{[6],[7]}). This is due to the fact that the upper layers are still optically active, i.e. they absorb photons which recombine radiatively, thereby emitting a photon which then can be re-absorbed in the layer below and that is possibly the active junction. This phenomenon is called photon recycling or optical coupling. Photon recycling in reference solar cells shall be removed since the photon recycling leads to a component cell which is not identical to the respective subcell in a multi-junction cell, and - even worse - results in an unacceptable non-linearity of the reference solar cell (cp. [Figure 2](#)^[6]).

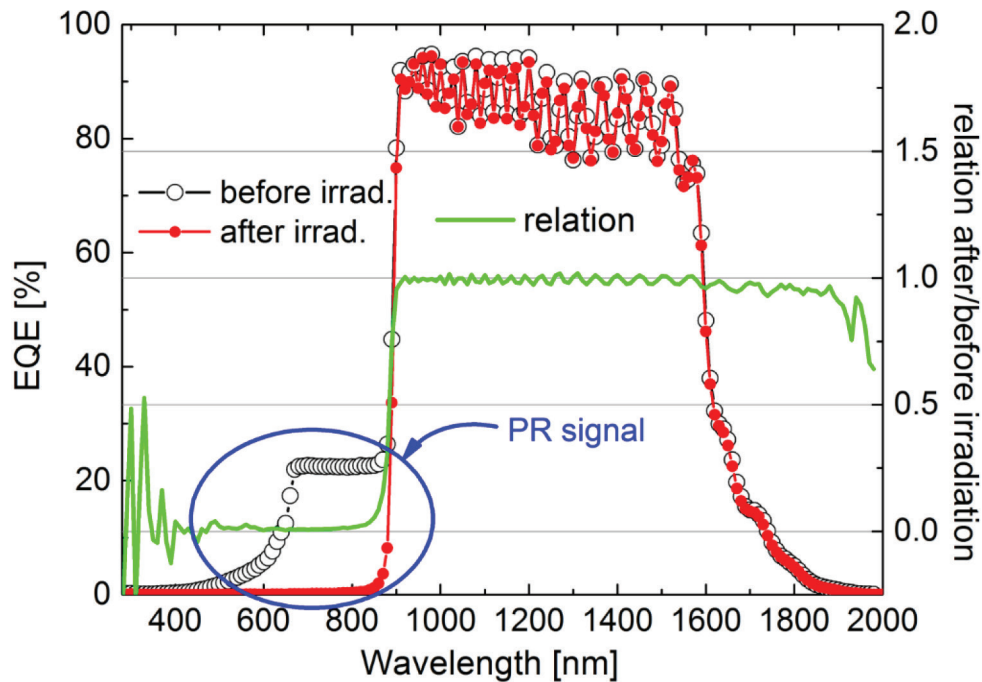


Figure 1 — EQE of a Ge component cell before and after (electron) irradiation. The photon recycling from the upper layers is suppressed due to the degradation of the material quality after irradiating the sample. The green line corresponds to the right axis and gives the relationship between the measurement performed after and before radiation.

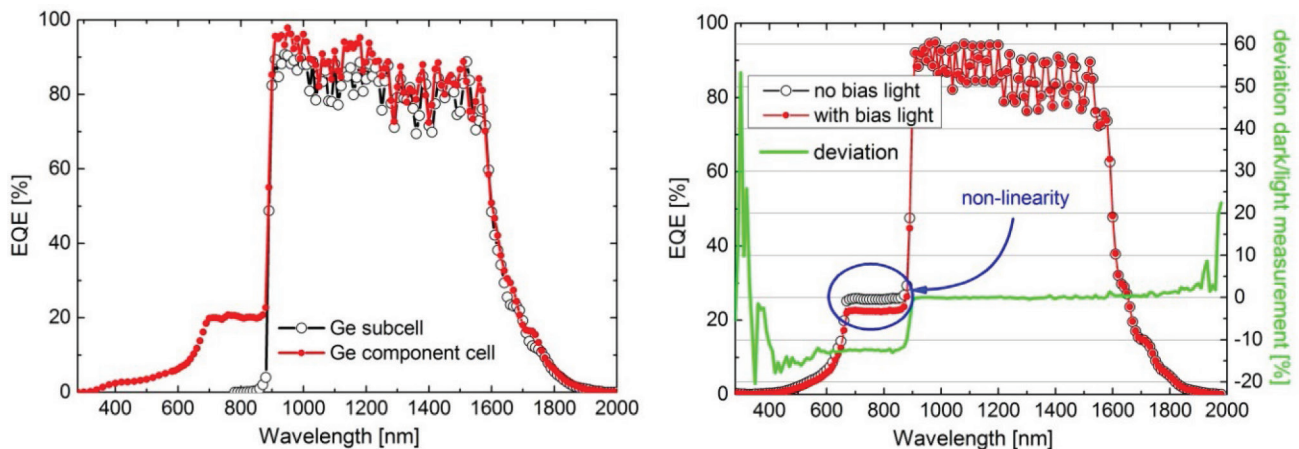


Figure 2 — left: Comparison of the EQE of the Ge subcell (as part of triple-junction solar cell) and the corresponding component cell; right: EQE of a Ge component cell measured with bias light and in the dark. While the measurement is perfectly reproduced in the region where the Ge subcell in a 3J cell is typically sensitive (from 900 nm on) the EQEs differ by over 10 % in the other regions. This is evidence to the fact that the photon recycling and thus the spectral responsivity in this region depend on the level of intensity.

As shown in [Figure 1](#) photon recycling can be removed by irradiating the solar cells. This is quite simple for Ge cells since the Ge cell itself is almost not affected by the particle irradiation. However, for other layers the particle irradiation might not only remove the photon recycling but also would change the EQE of the active cell. In order to avoid that, it is suggested to try to irradiate these cells with low energy protons which stop in the layers above the active junction.

5.2.2 Multi-junction AM0 primary reference solar cell

A reference device with more than one junction being electrically active. Multi-junction primary reference solar cells are typically used as final verification when adjusting sun simulators to AM0 conditions (using single-junction component cells). The reference value in case of multi-junction reference solar cells is typically not limited to the short circuit current but the full I-V curve is required.

NOTE Multi-junction AM0 primary reference solar cells can only be calibrated using high altitude methods. This is due to the fact that solar simulators on ground can never be matched closely enough to the AM0 spectrum and a mismatch correction on the measured calibration value is considered to introduce a too high uncertainty for multi-junction solar cells.

5.2.3 High altitude calibration procedures

Calibration procedures based on quasi extraterrestrial AM0 conditions. Hereby, “quasi extraterrestrial AM0 conditions” shall be understood as conditions found above the tropopause (around 15 km¹⁾ above sea level).

NOTE High altitude AM0 conditions are characterized by actually using the sun as a calibration reference. However, according to the international definition of primary reference standards and primary reference measurement procedures the sun cannot be considered a primary reference standard unless it is by convention agreed that it is defined as an artefact for the AM0 irradiance level. This has been done in the definitions paragraph 3.40. High altitude AM0 conditions are obviously the most ideal conditions to calibrate primary reference solar cells and are considered the only conditions under which multi-junction solar cells can adequately be calibrated. However, it shall be highlighted that also methods that are based on high altitude calibrations have to apply certain corrections which strongly depend on the altitude at which the solar cells are calibrated.

Examples for high altitude calibration methods, using high altitude balloon or aircraft, can be found in [Annex A](#).

5.2.4 Synthetic calibration procedures

Calibration procedures that are based on conditions found on ground and characterised by applying as a reference a radiometer, a standard detector or a standard light source traceable to SI units. Synthetic AM0 methods are restricted to the calibration of single-junction solar devices (which includes component solar cells).

Examples for synthetic calibration methods can be found in [Annex A](#).

5.3 Selection

Solar cells shall be irradiated with one solar constant (1 361,1 W/m² and AM0 spectrum – see [Annex B](#)) for 48 h. The cells shall be kept at 25 °C ± 5 °C during the test. Electrical performance measurements shall be performed on the cells before and after this test to demonstrate their stability.

AM0 primary reference solar cells shall be stable devices, i.e. their photovoltaic characteristics shall not change from the initial calibration to re-evaluation by more than 1 %.

The output signal of the AM0 primary reference solar cell shall vary linearly with irradiance (see NOTE concerning component cells in [5.2.1](#)), as defined in IEC 60904-10, over the range of interest.

NOTES

- If the final purpose of the AM0 primary reference solar cells is to be used for multi-junction cell measurements, a set of primary reference solar cells contains as a minimum the respective component cells. The adjustment of sun simulators used for measuring multi-junction solar cells are typically performed with component cells. Sometimes a final check of the simulator settings is performed with a multi-junction primary reference cell. Thus, a complete set of primary reference solar cells contains the full multi-junction plus the respective component cells.
- It has to be considered that end of life (EOL) performance of solar cells in space applications plays an important role. Therefore, an enhanced set of primary reference solar cells would also contain additional subsets of cells which have been irradiated to different fluence levels.

1) Any method that flies below 30km altitude might suffer from higher uncertainties which are related to non-linearities in the Langley extrapolation when performing the residual ozone corrections [15].

- It is recommended to provide spare cells for each AM0 primary reference solar cell.

5.4 Temperature measurement

Means shall be provided for measuring the AM0 primary reference solar cell device or junction temperature to an accuracy of ± 1 °C.

5.5 Electrical connections

Any measurement resistor incorporated into the AM0 primary reference solar cell shall be a high temperature stability resistor with a low value in order to allow the cell to operate close to its short-circuit current (the requirements defined in IEC-60904-2 on built-in shunt resistors apply). On the other hand, the electrical connections to the AM0 primary reference solar cell without resistance shall consist of a four-wire contact system (Kelvin probe). In accordance with the requirements of IEC 60904-1 the 4-wire connection of the primary reference solar cell shall start at the cell bus bars.

5.6 Calibration

Each AM0 single-junction primary reference solar cell shall be calibrated in terms of its short-circuit current at STC.

Each AM0 multi-junction primary reference solar cell shall be calibrated by determining the full I-V curve of the cell at STC.

Some possible methods of calibrating AM0 primary reference solar cells are described in [Annex A](#).

Whenever current-voltage characteristics are recorded in the frame of the respective calibration method the requirements defined in IEC 60904-1 shall be followed (using the AM0 spectrum as the reference spectrum – see [Annex B](#)).

The relative spectral responsivity and the temperature coefficient of each AM0 primary reference solar cell shall be measured in accordance with IEC 60904-8, IEC 60904-8-1 and IEC 60891 (using the AM0 spectrum as the reference spectrum – see [Annex B](#)).

NOTE With the recently issued IEC 60904-8-1 a standard is now available that covers methods to measure spectral responsivity of multi-junction solar cells. Other documents that can be read in conjunction are [\[8\]](#), [\[9\]](#), [\[10\]](#), [\[11\]](#).

5.7 Data sheet

Each time an AM0 primary reference solar cell is calibrated, the following information shall be recorded on a data sheet:

- identification number
- type (high altitude AM0 primary reference solar cell or synthetic AM0 primary reference solar cell)
- cell manufacturer
- material type
- type of package
- type and dimension of cell(s)
- circuit diagram, in particular of any connectors
- calibration organization
- site and date of calibration
- method of calibration (refer to standard)

- radiometer or standard lamp characteristics (where applicable)
- simulator characteristics (where applicable)
- type of temperature sensor (where applicable)
- relative spectral responsivity
- temperature coefficient of short-circuit current
- calibration value (or full I-V curve) at AM0 reference conditions
- measurement conditions
- measurement uncertainty
- shunt resistor nominal resistance and temperature coefficient (where applicable)

For reference cells without fixed electrical connection to the cell, the following information shall be recorded on the data sheet:

- illustration of type, shape and location of electrical contacts during calibration

5.8 Marking

Each AM0 primary reference solar cell shall carry a clear, indelible identification number for cross-reference to its data sheet.

5.9 Packaging

For packaging of AM0 primary reference solar cells the respective chapter in IEC 60904-2 applies. Examples of suitable cell packages are shown given in [Annex D](#).

Note Ideally, the packaging of AM0 primary reference cells shall reflect the intended application, i.e. if the primary reference cells and derivatives (secondary reference cells and working references) thereof are going to be used to characterise bare solar cells, the primary cells shall also be bare cells whereas solar cell assemblies (solar cells with coverglasses) shall be characterised using reference cells with respective coverglasses.

5.10 Care of AM0 primary reference solar cells

All AM0 primary reference solar cells shall be kept at temperatures below 50 °C during operation and storage. The cells should be kept in darkness during extended storage periods.

The window of a packaged reference device shall be kept clean and scratch-free.

Uncovered AM0 primary reference solar cells shall be preserved from damage, contamination and degradation. A possible way is storing them under dry nitrogen conditions.

AM0 primary reference solar cells shall be verified on an annual basis (by cross-checks against other primary reference solar cells). AM0 primary reference solar cells in frequent use shall be cross-checked at shorter intervals. If there is a change in the calibration values (either I_{SC} or - in case of multi-junction solar cells - any other photovoltaic parameter derived from the full I-V curve) beyond ± 1 % the cells should be recalibrated.

A reference device exhibiting any defect which might impair its function shall not be used.

If the calibration value of a reference device has changed by more than 5 % of the initial calibration it shall not be used as a reference device.

NOTE This paragraph follows closely the recommendations given in the respective chapter of IEC 60904-2.

6 General requirements and procedures for AM0 secondary reference solar cells

6.1 General

AM0 secondary reference solar cells shall be calibrated in simulated sunlight against an AM0 primary reference solar cell.

In order to minimize measurement uncertainties AM0 primary reference solar cells and AM0 secondary reference solar cells shall be manufactured in an identical way as the AM0 primary reference solar cells and hence have the same properties:

- AM0 primary reference solar cells and AM0 secondary reference solar cells shall be spectrally matched or at least very similar in accordance to the definition given in 3.
- AM0 primary reference solar cells and AM0 secondary reference solar cells shall have identical active area.
- AM0 primary reference solar cells and AM0 secondary reference solar cells shall have identical angle of incidence effects, if the simulated sunlight illumination contains a significant proportion of diffuse irradiance ($E_{\text{diff}}/E_{\text{total}} > 0,1$).

6.2 Solar simulator

The solar simulator shall be classified in accordance with IEC 60904-9 in terms of spectral distribution match, irradiance non-uniformity on the test plane and temporal instability. With respect to the spectral distribution match, however, the following adaption is made: The spectral distribution match of the solar simulator is defined by the deviation from AM0 reference spectral irradiance as laid down in this standard. For the following wavelength intervals of interest, the percentage of total irradiance (up to the wavelength of interest) is specified in [Table 1](#). To verify the spectral distribution of the solar simulator the spectral irradiance has to be measured in accordance with [Annex C](#).

The calibration of AM0 secondary reference solar cells shall preferably be performed under a Class AAA simulator. However, a lower class simulator with respect to the spectral distribution match is also acceptable when the requirement for spectral match of solar cells (cp. 3) is met. A detailed uncertainty analysis shall be performed in any case and the claimed accuracy of the calibration value shall be reported.

Table 1 — Wavelength range of interest for solar cell measurements, total irradiance and respective percentage of total irradiance of various wavelength intervals within this range.

Wavelength interval [nm]	Total Irradiance between indicated wavelength intervals [W/m ²]	Percent of Total Irradiance for between indicated Total Range of AM0 spectrum (280 nm – 2 000 nm) within various wavelength intervals
280 - 2 000	1 270,67	100
280 - 400	102,15	8,0
400 - 500	188,85	14,9
500 - 600	184,77	14,5
600 - 700	158,17	12,4
700 - 800	126,55	10,0
800 - 900	100,43	7,9
900 - 1 000	80,79	6,4
1 000 - 1 100	65,59	5,2
1 100 - 1 200	53,66	4,2
1 200 - 1 300	44,83	3,5
1 300 - 1 400	37,66	3,0
1 400 - 1 500	31,75	2,5
1 500 - 1 600	26,85	2,1

Table 1 (continued)

Wavelength interval [nm]	Total Irradiance between indicated wavelength intervals [W/m ²]	Percent of Total Irradiance for between indicated Total Range of AM0 spectrum (280 nm – 2 000 nm) within various wavelength intervals
1 600 – 1 700	22,52	1,8
1 700 – 1 800	18,45	1,5
1 800 – 1 900	15,09	1,2
1 900 – 2 000	12,55	1,0

6.3 Calibration procedure

- 1) Before the calibration, measure the relative spectral responsivity and temperature coefficient of short-circuit current of the AM0 primary reference solar cell (if not known) and of the AM0 secondary reference solar cell, using the procedures specified in IEC 60904-8 and IEC 60891 (using the AM0 spectrum as the reference spectrum – see [Annex B](#)).
- 2) Calculate the mismatch factor in accordance with IEC 60904-7. In case a solar simulator is used, the solar simulator settings shall be adjusted applying the spectral mismatch correction.
- 3) Mount the AM0 primary and the AM0 secondary reference solar cells coplanar and in close proximity on the same mount. Adjust the mount so that the solar beam or centerline of the simulator beam is normal to the cell surfaces within $\pm 5^\circ$. Non-uniformity of the irradiance across the two lateral positions of the AM0 primary and the AM0 secondary reference solar cells shall be corrected for. In case a solar simulator is used, measurements of AM0 primary and secondary reference solar cell can be also done subsequently, by placing the two cells one after the other at the same position under the solar simulator. Temporal stability of the simulator shall be monitored and any deviations between the two measurements shall be corrected in accordance with IEC 60891.
- 4) Connect to the current and temperature measuring instruments. If possible, control the cell temperature at $25^\circ\text{C} \pm 1^\circ\text{C}$. If it is not practicable to control the temperature of the cells, readings of output signals must be subsequently corrected to 25°C in accordance with IEC 60891 (using the AM0 spectrum as the reference spectrum – see [Annex B](#)).
- 5) Record simultaneous readings of the short-circuit currents and temperature of both standard solar cells (or perform readings of each cell subsequently at the same position under the solar simulator).
- 6) Repeat step (5) until five successive sets of readings are obtained in which the ratios of the short-circuit currents, corrected to 25°C , do not vary by more than $\pm 1\%$.
- 7) From the acceptable data, calculate the mean ratio:

$$\frac{\text{Short – circuit current of AM0 secondary reference cell at } 25^\circ\text{C}}{\text{Short – circuit current of AM0 primary reference cell at } 25^\circ\text{C}}$$

- 8) Multiply the calibration value of the AM0 primary reference solar cell by the calculated mean ratio to obtain the calibration value of the AM0 secondary reference solar cell.

NOTE This paragraph follows closely the recommendations given in the respective chapter of IEC 60904-2.

NOTE The method above is applicable to single-junction cells only. For AM0 secondary reference multi-junction cells the respective method in {new measurement handbook} shall apply.

7 AM0 solar spectral irradiance reference

7.1 General

This clause specifies the AM0 reference high altitude solar spectral irradiance.

7.2 AM0 solar spectral irradiance

The AM0 reference solar spectral irradiance for the purpose of this International Standard is illustrated in Figure 4. The spectral data is taken from^[12] which results in an integrated value of the total solar irradiance of 1 361,1 W/m² at AM0, on a plane surface under normal incidence.

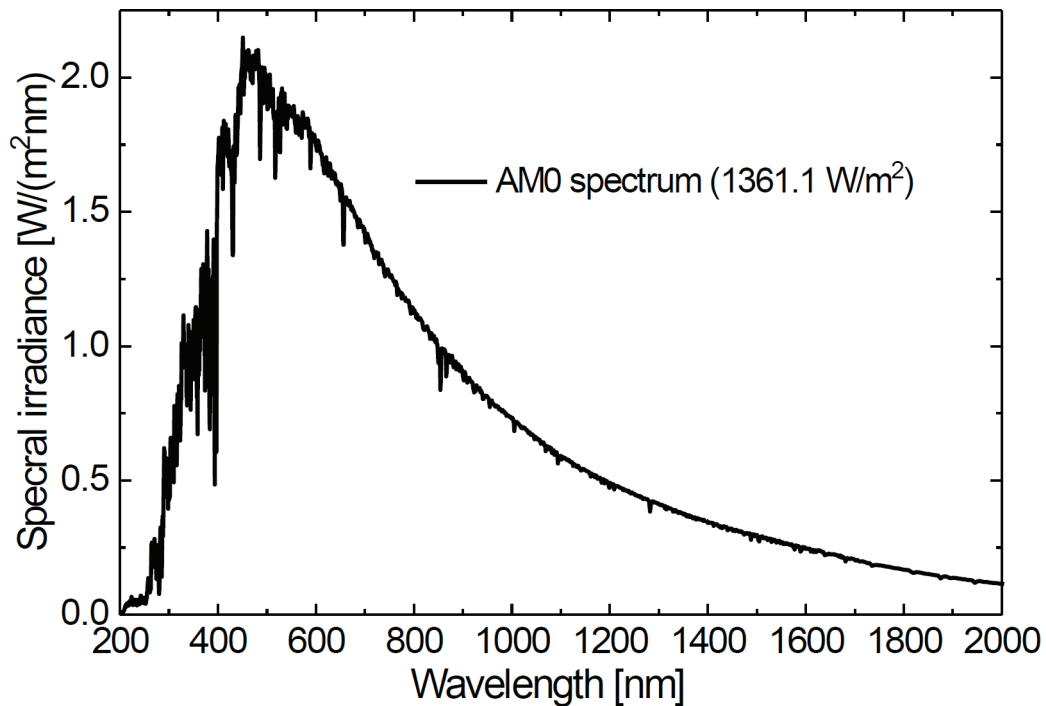


Figure 3 — AM0 solar spectral irradiance (part of the distribution)

Annex A (informative)

Calibration methods for AM0 primary reference solar cells

A.1 General

This annex provides information about validated calibration methods for AM0 primary reference solar cells. The uncertainty analysis for each calibration procedure is provided (applicable to single-junction solar cells). Any calibration method (whether listed here or not) has to clearly indicate the measurement uncertainty based on a systematic uncertainty analysis.

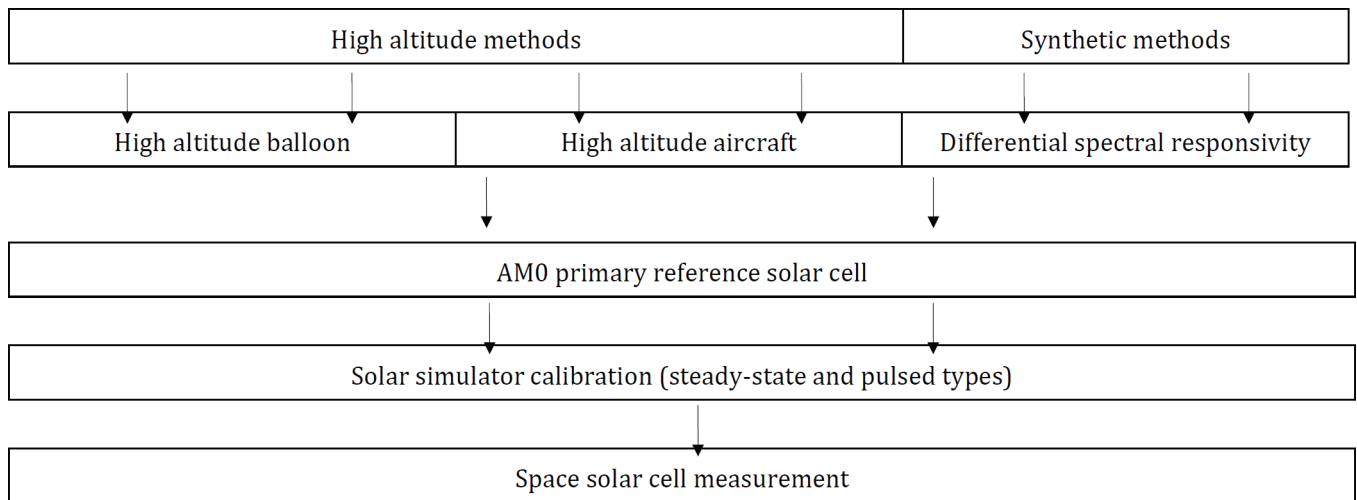


Figure A.1 — Calibration methods for (primary) air mass zero (AM0) standard cell

A.2 High altitude calibration methods

- 1) High altitude balloon flight calibration method
- 2) High altitude aircraft calibration method

A.3 Synthetic calibration methods

- 1) Differential spectral responsivity calibration method
- 2) Global sunlight calibration method

A.4 Calibration methods of AM0 primary reference solar cells using high altitude methods

A.4.1 High altitude balloon flight calibration method (CNES)

A.4.1.1 Description

Since 1975, CNES (French National Space Research Centre) has been involved in the calibration of space solar cells by producing AM0 standard solar cell. Calibrations are performed on-board stratospheric

balloons flying at high altitudes where the solar spectral irradiance is close to AM0. CNES calibrates primary standards with stratospheric balloon flights since 1976. Safety rules limited the flight opportunities, so it was not possible to propose the calibration service since 2005.

A new balloon facility has been developed in CNES with the help of ESA in order to calibrate space solar cells with high accuracy. The first flight was carried out in April 2017 in Alice Springs, Australia.

A.4.1.1.1 Nacelle and balloon

A.4.1.1.1.1 Balloon

The open stratospheric balloon has a volume of 400 000 m³ (about 130 m diameter) which allows a flight altitude of at least 30 km for a 750 kg load.

The 2-wire link between the balloon and the nacelle is 136 m long for the first flight.

A.4.1.1.1.2 CARMEN platform

The CASOLBA (CALibration SOLaire BALLon) payload is mounted on the CARMEN platform (or its smaller variant CARMENCITA).

The CARMEN nacelle is a heavy multi-mission facility which provides all facilities: accurate pointing, energy, TM/TC and data storage. The sun pointing accuracy is 1° in azimuth and 0,5° in elevation.

The maximum weight is 1 100 kg. Up to 4 scientific missions can fly simultaneously, with as many more smaller ones as weight and volume allow.

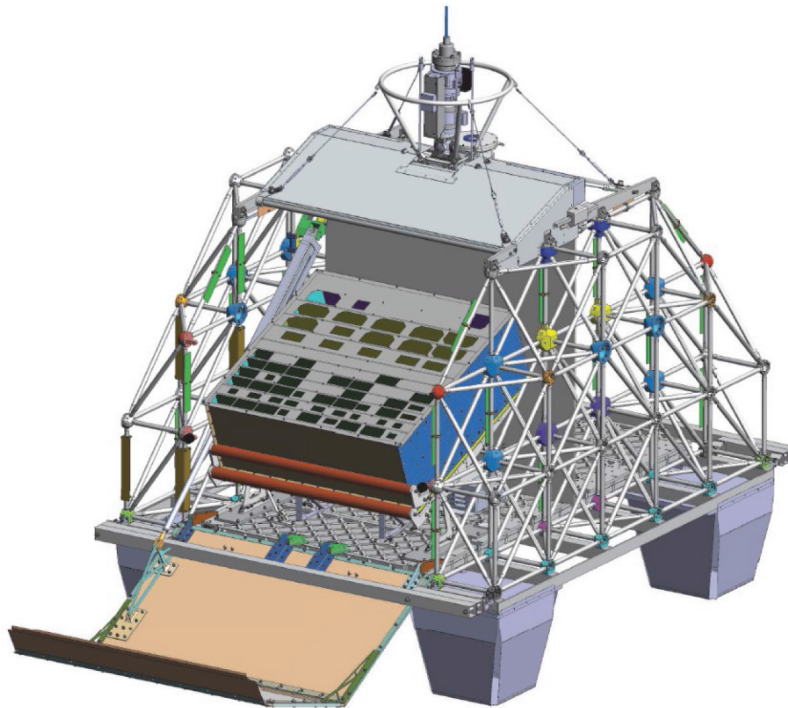


Figure A.2 — plate and collimator in the CARMENCITA nacelle

A.4.1.1.2 CASOLBA payload

The thermal control is fully passive. The plate is cooled during ascent and non-pointed phases of the flight. The device temperature of each cell is measured accurately by AD590M thermal sensors integrated in the cell holder.

The CASOLBA payload is a 1 m² plate carrying up to 88 cells, pointed towards the sun with accuracy better than 1°. A 320 mm high baffle avoids any parasitic light coming from the balloon and from the earth limbo.

The shape of the solar cells is reproduced on the front mask. The mask allows a good collimation and avoids excessive heating of the cells.



Figure A.3 — plate, collimator and front mask before painting

A.4.1.1.2.1 Cell holders

Each cell is mounted on a specific holder. The sun-oriented plate is able to support 63 mid-size holders (for cells up to 42*85 mm²), and 25 large-size holders (for cells up to 71*148 mm²). Double-size holders can be used if needed. Each holder carries a temperature sensor (AD590M) in contact with the centre of the cell, a protection by-pass diode, a hood for mechanical protection on ground and a 6-pin connector. It is possible to mount NSCAP (NRL-NASA-AFRL Near Space Characterization of Advanced Photovoltaics) or every type of cell holder on the plate by the means of standard size adaptors.

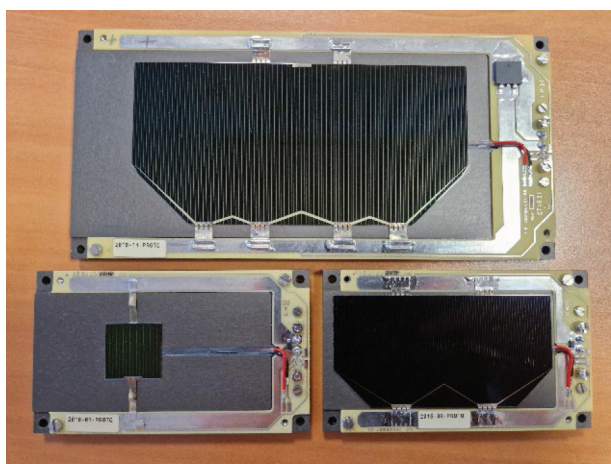


Figure A.4 — 2×6, 8×4 and 2×2 cm² cells on holders

A.4.1.1.2.2 Measurement system

The measurement system is based on CNES know-how, with a passive thermal control (the temperature of the cells decreases during the ascent and during non-pointed periods). The current-voltage curves (100 points from V_{oc} to I_{sc} – and 100 points from I_{sc} to V_{oc}) of the cells are measured continuously during the sun-pointed periods. The temperature of the cell is measured at the beginning and at the end of the I-V curve measurement. The temperature range is [10 °C; 40 °C] or more.

The measuring electronics is shared into 3 MCCA (Module de Caractérisation de Cellules Solaires) boxes. Each box is able to measure successively 32 solar cells.

The electronics is able to measure the temperature, the cell voltage up to 5,7 V (low voltage up to 0,75 V; high voltage up to 5,7 V) and cell current up to 2,8 A (low currents up to 0,25 A; high currents up to 2,8 A).

A.4.1.2 Measurement

After selection of the cell to measure, the sequence hereafter is followed:

- Acquisition of the cell temperature
- Acquisition of the cell open circuit voltage
- Acquisition of 100 I/V measurement points between the cell open circuit voltage and -0,3 V. In order to measure the whole I/V curve despite the harness and shunt resistor losses, the variable power supply is able to provide positive and negative voltage.
- Acquisition of 100 measurement points between -0,3 V and open circuit voltage.
- Measurement of the cell temperature.
- Auto-calibration of the analog-digital converter
- Selection of the following cell

The measurement time is one second per cell. The measuring session is the measurement of the characteristics of all the cells, the measuring sequence is all the sessions of a sun-pointed period. Up to 3 sequences can be performed during the flight at different sun elevation or different altitudes in order to have a better view on the effect of residual atmosphere and improve the accuracy of the corrections. Between the measuring sessions, the nacelle is pointed out of the sun direction and the cells are cooled down.

All the flight data will be provided to the users: rough current-voltage curves, temperature and current in the temperature sensor, but also corrections of the sun-earth distance and atmospheric spectral absorption (air mass), altitude and localisation.

A.4.1.2.1 Correction of the measurements

In order to calculate the short circuit current of the cell at air mass zero, the value of the current is corrected by means of two coefficients:

$$k_n = \frac{\int s(\lambda) \cdot G_{AM0}(\lambda) d\lambda}{\int s(\lambda) \cdot G_{AMx}(\lambda) d\lambda} \quad (A.1)$$

where

kn is the residual atmosphere at the balloon's altitude;

$s(\lambda)$ is the spectral responsivity of the cell;

$G(\lambda)$ is the spectral irradiance;

AM_x is the air mass at the altitude and sun elevation during the measurement;

G_{AMx} is calculated using the latest version of the SMARTS model^{[13], [14]}.

At the current flight altitudes and sun elevations, the correction is lower than 1 % from the short circuit current

For multijunction cells, the correction is calculated with respect to the current limiting junction

The correction is only valid for the reference temperature of 25 °C (for the spectral responsivity)

The measurements sequences are repeated two or three times at different air masses in order to improve the knowledge of the kn correction

$$ks = d^2 \quad (A.2)$$

where

ks is the variation of illumination caused by the varying Earth-Sun distance over the year;

d is the sun-earth distance the day of the flight in astronomic units;

The corrections are applied only on the short circuit current. Then, the corrected I/V curve can be slightly different from a real I/V curve measured at 1,00 AM0.

A.4.1.3 Uncertainty analysis

The preliminary uncertainty budget is the following (values assume $k=1$):

- Error linked to the measuring system:
 - High voltage range [0;5,7 V]: 3,28 mV
 - Low voltage range [0;0,75 V]: 0,6 mV

Uncertainty on current:

- Error linked to the measuring system:
 - High current range [0;2,8A]: 1,12 mA
 - Low current range [0;0,25A]: 64 μ A
- Error linked to misalignment, pointing accuracy, residual light flux and internal reflexions
 - 0,1 %

Uncertainty on temperature:

- Error linked to the measuring of the AD590 current: 0,11 μ A
- Error linked to calibration and measuring system: 0,6 °C

Including other sources of uncertainty such as stray light an overall standard uncertainty on the calibration value of 0,7 % ($k=1$) shall be assumed.

A.4.1.4 Supply

Each calibrated cell is returned on its holder with every corrected and uncorrected flight data.

A.4.2 High altitude aircraft calibration method (NASA-GRC)**A.4.2.1 Principle**

A.4.2.2 Short-circuit current (I_{sc}) is obtained by exposing the solar cells directly to the Sun at high altitudes. Change in I_{sc} is measured while descending from the aircraft's altitude ceiling (~65 k ft). I_{sc} is plotted versus the changes in air mass, then Air-Mass-Zero (AM_0) estimation of I_{sc} is extrapolated.

The solar elevation angle is held constant by conducting the measurements at solar noon over a small period of time. The ambient pressure changes with altitude.

A.4.2.3 Apparatus

The following apparatus is required:

1. An aircraft capable of flight to 21 km altitude and descent controlled in roll, pitch, and yaw axes to 1°
2. 5:1 or better collimating tube mounted in the aircraft
3. A computer system for control, data acquisition (DAQ), and storage
4. A calibrated source measure unit and switching unit
5. A calibrated high sensitivity absolute pressure transducer
6. A calibrated cockpit-mounted sun sight

A.4.2.4 Environmental conditions

The calibration must be carried out in the stratosphere the second layer of the atmosphere between 20 km and 50 km above the Earth. The time of year that will provide the largest possible Sun elevation angle shall be selected. Cell temperature shall be $25\text{ °C} \pm 1\text{ °C}$ during calibration.

A.4.2.5 Test procedure

- I. Configure an optimal test cell layout with Devices Under Test (DUTs) and NASA Standards onto temperature-controlled test plate.
- II. Tune the DAQ system according to the test cell layout and perform a pre-flight test run ensuring all cells have proper ohmic connections to the measurement instruments.
- III. Determine whether the proper atmospheric conditions have been met for the flight. The upper atmosphere data must be obtained at 1 200 GMT on the day of the calibration flight from at least three relevant locations. Check with aircraft operations about the suitability of surface weather conditions for safe flight operations.
- IV. Calculate and adjust proper tube angle setting for the collimating tube in aircraft and pilot sun sight using data from the NOAA Solar Calculator²⁾.
- V. Mount test plate to collimating tube in aircraft. Perform a full test run of the aircraft system, including computer software and hardware, DAQ, temperature control, pressure transducer, and pilot interface switches. Update software on the computer, if necessary.
- VI. After the flight, remove the cell mounting plate from the collimating tube and extract calibration data from the computer. Visually inspect all aircraft calibration equipment, and test cells.

2) NOAA Solar Calculator: <https://gml.noaa.gov/grad/solcalc/>

VII. Plot the logarithm of I_{sc} versus the air mass number. Correct for I_{sc} calibration values using the Langley plot method and Heliocentric Distance correction.

A.4.2.6 Uncertainty analysis

Table A.1 — Uncertainty summary of aircraft calibration method (NASA-GRC)

Source of error	Effect on I_{sc} , %
Non-normal incidence to sun	0,011
Non-simultaneous pressure and current readings	0,15
Cell temperature uncertainty	0,08
Voltmeter one year accuracy	0,004 1
Fluctuations in the ozone correction	0,082 8
Data interpretation uncertainty	0,15
Uncertainty within a laboratory (GaAs cell)	0,574 5
Uncertainty within a laboratory (silicon cell)	0,511
Systematic error between laboratories (GaAs cell)	0,741
Systematic error between laboratories (silicon)	0,93
Total systematic uncertainty (GaAs cell)	0,97
Total systematic uncertainty (silicon cell)	1,09
Total random error	0,042 6

A.5 Calibration methods of AM0 primary reference solar cell using synthetic methods

A.5.1 Differential Spectral Responsivity (DSR) Calibration method (PTB)

A.5.1.1 General

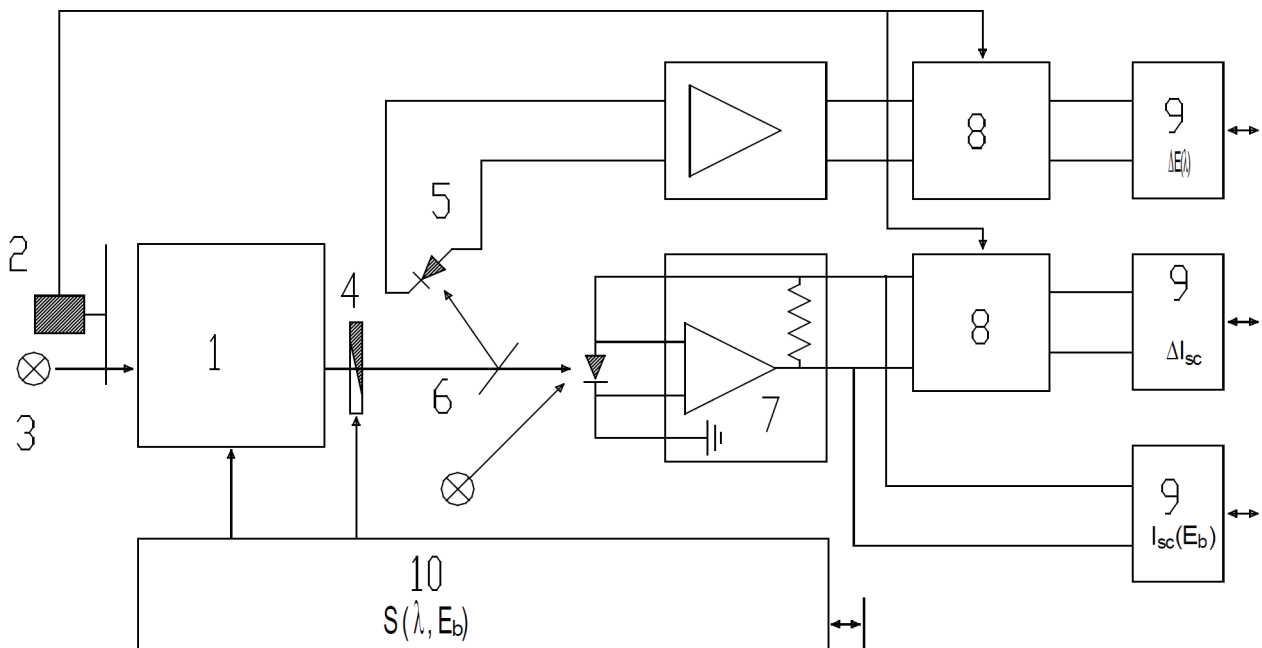
Traceability is based on a calibration of spectral responsivity based on standard detectors directly traceable to SI units. The calibration value is computed from the measured absolute spectral responsivity of the PV reference device (expression used in this chapter equivalently for “primary reference solar 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 PV reference device concerning linearity or spectral match.

A.5.1.2 Equipment

The following apparatus is required (see [Figure A.5](#) and [A.6](#))

- a monochromator producing chopped spectral irradiance within the wavelength range covering the spectral responsivity of the PV reference device to be calibrated, with a traceable wavelength setting;
- 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). Alternatively, a tuneable or white light cw-Laser source with a continuously available spectral range from 280 nm to 2 000 nm;
- 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 $\pm 3\%$ within the active area of the device to be calibrated;
- comment: The monochromatic beam from [A.5.1.2. 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 $(25 \pm 1)^\circ\text{C}$;
- j) means for measuring the AC short-circuit currents of the PV reference device, 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 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.5.1.3. f\)](#).



Item List			
Item Number	Description	Item Number	Description
1	Monochromator	6	Beam splitter
2	Optical chopper	7	Current-voltage converter
3	Light source	8	Lock-in amplifier
4	Shutter	9	Digital voltmeter
5	Monitor photo-diode	10	Computer for data aquisition

Figure A.5 — Block diagram of differential spectral responsivity calibration superimposing chopped monochromatic radiation and DC bias radiation.