



**International
Standard**

ISO 20256

**Space systems — Solar cells —
Calibration procedures**

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Foreword

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

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

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.

The primary calibration methods given in [Annex A](#) serve as examples of acceptable calibration techniques.

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Space systems — Solar cells — Calibration procedures

1 Scope

This document specifies the requirements and procedures for the calibration of primary and secondary reference solar cells under the air mass zero (AM0) spectrum. It is applicable to both single-junction and multi-junction solar cells.

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 60904-2, *Requirements for photovoltaic reference devices*

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

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*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60904-7, IEC 60904-10 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: The absolute cavity radiometer is 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 m_{AM} is given by:

$$m_{AM} = \left(\frac{P}{P_0} \right) \times (1/\sin\theta)$$

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, in degrees.

3.3

air mass zero

AM0

absence of atmospheric attenuation of the solar irradiance at one *astronomical unit* (3.6) from the Sun

3.4

AM0 standard solar cell

calibrated *solar cell* (3.26) used to measure irradiance or to set simulator irradiance levels in terms of an *air mass zero (AM0)* (3.3) reference solar *spectral irradiance* (3.28) distribution

3.5

angle of incidence

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

3.6

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

[SOURCE: ISO 21348:2007, 2.1, modified — The abbreviated term "ua" and Note 1 to entry have been removed.]

3.7 centroidal wavelength

λ_g
wavelength that represents the band

$$\lambda_g = \frac{\int_0^{\infty} \lambda R(\lambda) d\lambda}{\int_0^{\infty} R(\lambda) d\lambda}$$

where

λ is the wavelength in nm;

$R(\lambda)$ is the response of spectroradiometer to monochromatic light with a wavelength of λ and of constant radiant flux

Note 1 to entry: This characteristic applies to input optics having a band sensitivity to wavelength.

3.8 junction temperature

T_j
temperature of p-n junction in a *solar cell* (3.26) that affects the performance, conversion 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.

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* (3.26), with only one active junction and the same *spectral responsivity* (3.30) as one *sub cell* (3.32) of a multi-junction solar cell

3.10 current-voltage characteristics

relationship between the output current of a *solar cell* (3.26) and the output voltage, at a particular temperature and irradiance

$$I = f(V)$$

where I is the output current and V is the output voltage

3.11 device temperature

T_d
temperature of a *solar cell* (3.26) 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* (3.8) 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 is 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. Nominally identical cells (in terms of *spectral responsivity* (3.30) then have slightly different spectral responsivities when they are not adjusted to the same *junction temperature* T_j (3.8). This adds to the mismatch factor.

3.12 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/m².

[SOURCE: ISO 16378:2022, 3.6]

3.13 irradiation

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

[SOURCE: ISO 23038:2018, 3.6]

3.14 linearity

property that two physical quantities or properties vary linearly

EXAMPLE With respect to a *solar cell* (3.26), relation of short-circuit current with *irradiance* (3.12) shows linearity.

3.15 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 conversion efficiency of the *solar cell* (3.26) compared to a *single-junction solar cell* (3.25)

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.

3.16 open circuit voltage

V_{oc}
voltage, of a photovoltaic (PV) reference device, generated by a *solar cell* (3.26) without electrical loading at a particular temperature and *irradiance* (3.12)

3.17 primary reference solar cell

instrument which a laboratory uses to calibrate secondary references, compared at periodic intervals to a *secondary standard* (3.23)

Note 1 to entry: Often primary reference solar cells can be realised at much lower costs than secondary standards.

Note 2 to entry: Typically, a *solar cell* (3.26) is used as a reference solar device for the measurement of natural or simulated solar *irradiance* (3.12). In the context of this document the term “primary reference solar cell” is used (instead of primary reference).

3.18 primary standard

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

Note 1 to entry: 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.

Note 2 to entry: The World Radiometric Reference (WRR) as realized by the World Standard Group (WSG) of cavity radiometers is the accepted primary standard for the measurement of solar *irradiance* (3.12).

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)* (3.34) value shall be taken into account in the uncertainty budget.

3.19

pyranometer

radiometer normally used to measure global sunlight *irradiance* (3.12) 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.

3.20

pyrheliometer

radiometer, complete with a collimator, used to measure direct sunlight *irradiance* (3.12)

Note 1 to entry: This instrument is sometimes called normal incidence pyrheliometer (NIP).

3.21

relative spectral responsivity

$s(\lambda)_{\text{rel}}$
spectral responsivity (3.30) normalized to a specified reference value, s_m

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

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

3.22

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* (3.12) are photovoltaic (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]

3.23

secondary standard

device, which by periodical comparison with a *primary standard* (3.18), 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* (3.12) are cavity radiometers which participate periodically (normally every 5 years) in the International Pyrheliometer Comparison (IPC) with the WSG, thereby giving *traceability* (3.35) to WRR. Direct traceability to SI radiometric scale can also be available for these instruments.

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

3.24

short circuit current

I_{sc}
output current of a *solar cell* (3.26) in the short-circuit condition at a particular temperature and *irradiance* (3.12)

3.25

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 conversion 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.

3.26

solar cell

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

3.27

solar elevation angle

θ

angle between the direct solar beam and the horizontal plane

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

3.28

spectral irradiance

$E(\lambda)$

irradiance (3.12) per unit wavelength

Note 1 to entry: The spectral irradiance is expressed in $\text{W}\cdot\text{m}^{-2}\cdot(\text{nm})^{-1}$.

3.29

spectral match of solar cells

matching of *relative spectral responsivity* (3.21) of two *solar cells* (3.26)

3.30

spectral responsivity

$s(\lambda)$

short-circuit current (density) generated by unit *irradiance* (3.12) 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* (3.28) responsivity which refers to the short-circuit current generated by unit irradiance, the unit is $\text{A}\cdot\text{W}^{-1}\cdot\text{m}^2$.

3.31

STC

standard test conditions

test conditions at cell temperature of 25 °C under AM0 solar *spectral irradiance* (3.28)

3.32

sub cell

individual *solar cell* (3.26) junction in a *multi-junction solar cell* (3.15)

3.33

temperature coefficient of short-circuit current

α

change of the short-circuit current of a *solar cell* (3.26) as a function of the change of cell temperature

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

3.34 total solar irradiance 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* (3.6)

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]

3.35 traceability

requirement for any photovoltaic (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* (3.12) 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, modified — Note 1 to entry has been added.]

3.36 wavelength width of slit

effect of the transmission wavelength band on the spectroradiometer

$$b_i = \frac{w_i}{f_i \frac{d\theta_i}{d\lambda}}$$

where

b_i is the wavelength width of the entrance slit, in nm;
 w_i is the mechanical width of the entrance slit, in mm;
 $d\theta_i/d\lambda$ is the degree of dispersion of input side, in rad/nm;
 f_i is the focal length of the collimator, in mm;

$$b_0 = \frac{w_0}{f_0 \frac{d\theta_0}{d\lambda}}$$

where

b_0 is the wavelength width of the exit slit, in nm;
 w_0 is the mechanical width of the exit slit, in mm;
 $d\theta_0/d\lambda$ is the degree of dispersion of exit side, in rad/nm;
 f_0 is the focal length of input optics, in mm

4 Symbols and abbreviated terms

CNES	Centre national d'études spatiales (French Space Agency)
EQE	External quantum efficiency
ESA	European Space Agency
GMT	Greenwich mean time
NASA-GRC	National Aeronautics and Space Administration – Glenn Research Center
PTB	Physikalisch-Technische Bundesanstalt
PV	photovoltaic
SI unit	Système international d'unités (International System of units)
TM	telemetry
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 clause closely adheres to the philosophy described in IEC 60904-2 and IEC 60904-4 which shall apply with the amendments provided in [5.2](#) to [5.10](#).

5.2 Classification

5.2.1 General

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.

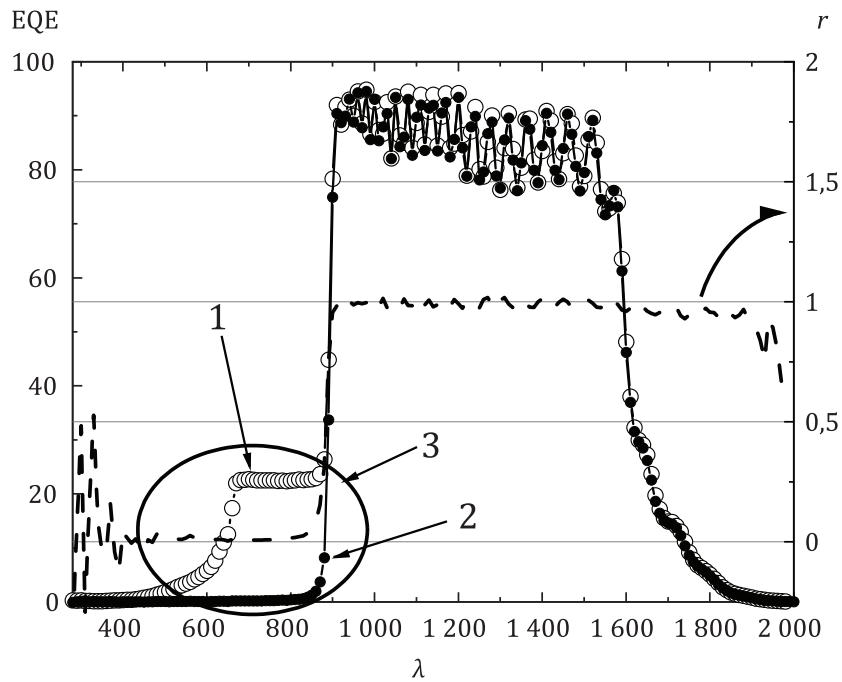
Traceable (synthetic) calibration procedures are necessary to transfer calibration from a standard or reference measuring (solar) irradiance (such as absolute cavity radiometer, pyrhelimeter and pyranometer or a reference photodiode traceable to SI) to a PV reference solar device. Such procedures shall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

5.2.2 Single-junction AM0 primary reference solar cell

A reference device with only one junction being electrically active.

This includes also component cells which are representative of a sub cell in a multi-junction solar cell. Note that component cells (unless being the top component cell) can show an unwanted sensitivity in a wavelength range in which the photons are absorbed by an upper electrically inactive layer ([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 sub cell in a multi-junction cell (Figure 2), and - even worse - results in an unacceptable non-linearity of the reference solar cell (Figure 3^[6]).



Key

- EQE external quantum efficiency, expressed in per cent
- λ wavelength, expressed in nanometres
- r ratio of signals after/before electron irradiation
- 1 measurement before electron irradiation
- 2 measurement after electron irradiation
- 3 wavelength region showing photon recycling

NOTE The photon recycling from the upper layers is suppressed due to the degradation of the material quality after irradiating the sample with electrons. The dashed line corresponds to the right axis and gives the ratio between the measurement performed after and before irradiation.

Figure 1 — EQE of a Ge component cell before and after (electron) irradiation