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**Space systems — Single-junction solar  
cells — Measurement and calibration  
procedures**

*Systèmes spatiaux — Cellules solaires simple jonction — Méthodes de  
mesure et d'étalonnage*

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## Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 15387 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

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## Introduction

This International Standard 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 use of solar photovoltaic cells in outer space. It introduces the principle of the air mass zero cell, which serves as a standard reference for primary calibration purposes. All further calibration is then compared to the results obtained with these cells.

The calibration procedures for primary solar cells are established, as well as the corresponding measuring methods for secondary cells. Calibration methods using extra-terrestrial and synthetic techniques are given. Comparative tests are in preparation.

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# Space systems — Single-junction solar cells — Measurement and calibration procedures

## 1 Scope

This International Standard specifies measurement and calibration procedures of single-junction space solar cells only. The main body of this international standard specifies the requirements for Air Mass Zero (AM0) standard calibration and the relative measurement procedures are provided as annexes.

## 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 60891, *Procedures for temperature and irradiance corrections to measured current-voltage (I-V) characteristics of crystalline silicon photovoltaic (PV) devices*

IEC 60904-1, *Measurement of photovoltaic current-voltage (I-V) characteristics*

IEC 60904-2, *Requirements for reference solar cells*

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

IEC 60904-7, *Computation of spectral mismatch error introduced in the testing of a photovoltaic (PV) device*

IEC 60904-8, *Guidance for the measurement of spectral response of a photovoltaic (PV) device*

IEC 60904-9, *Solar simulator performance requirements*

IEC 61798, *Linearity measurement methods*

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

### 3.1

#### 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 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:

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

where

$P$  = local air pressure in pascals;

$P_0$  =  $1,013 \times 10^5$ , in pascals;

$\theta$  = solar elevation angle (degrees).

### 3.2

#### air mass zero

##### AM0

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

### 3.3

#### 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

### 3.4

#### 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

### 3.5

#### angle of incidence

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

### 3.6

#### astronomical unit

##### AU

unit of length defined as the semi major axis of earth orbit

NOTE 1 AU = 149 597 890 km  $\pm$  500 km.

### 3.7

#### cell temperature

$T_j$

cell temperature as one of ambient air in absence of cell illumination or under short duration light pulse (flash)

NOTE  $T_j$  is not very different from the temperature of the cell exposed face.

### 3.8

#### current temperature coefficient

$\alpha$

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

NOTE  $\alpha$  is expressed in amperes per degree Celsius ( $A \cdot ^\circ C^{-1}$ ).

### 3.9

#### 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

### 3.10

#### current-voltage characteristics

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

NOTE  $I = f(V)$ .

**3.11****fill factor****FF**

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

NOTE  $FF = P_{\max}/(V_{\text{oc}} \times I_{\text{sc}})$ .

**3.12****irradiance**

radiant power incident upon unit area of surface

NOTE It is expressed in watts per square metre ( $\text{W}\cdot\text{m}^{-2}$ ).

**3.13****irradiation**

integration of irradiance over a specified period of time

NOTE It is expressed in megajoules per square metre ( $\text{MJ}\cdot\text{m}^{-2}$ ) per hour, day, week, month or year.

**3.14****linearity**

performance of a solar cell with respect to:

- the variation of the slope of short-circuit current to irradiance;
- the variation of the slope of open circuit voltage to the logarithm of irradiance;
- the variation of the slope of short-circuit current and open-circuit voltage to cell temperature; and
- the variation of relative spectral response at a specified voltage

**3.15****load current** $I_L$ 

current supplied by the solar cell at a particular temperature and irradiance, into a load connected across its terminals

**3.16****load voltage** $V_L$ 

voltage appearing across the terminals of a load connected to the terminals of the solar cell at a particular temperature and irradiance

**3.17****load power** $P_L$ 

power supplied to a load connected to the terminals of the solar cell at a particular temperature and irradiance;

NOTE  $P_L = V_L \times I_L$ .

**3.18****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  $P_{\max} = V_{\max} \times I_{\max}$

**3.19**  
**maximum power voltage**

$V_{Pmax}$   
voltage corresponding to maximum power at a particular temperature and irradiance

**3.20**  
**maximum power current**

$I_{Pmax}$   
current corresponding to maximum power at a particular temperature and irradiance

**3.21**  
**module**  
assembly of interconnected solar cells

**3.22**  
**open circuit voltage**  
 $V_{oc}$   
voltage across a solar cell with no load at a particular temperature and irradiance

**3.23**  
**ozone content**  
volume of ozone at standard temperature and pressure in a vertical column of the atmosphere

NOTE Ozone content is measured with a Dobson spectrophotometer.

**3.24**  
**pyranometer**  
radiometer normally used to measure global sunlight irradiance on a horizontal plane

NOTE 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.

**3.25**  
**pyrheliometer**  
radiometer, complete with a collimator, used to measure direct sunlight irradiance

NOTE This instrument is sometimes called normal incidence pyrheliometer, or NIP.

**3.26**  
**rated current**  
assigned value of current of a solar cell at the rated voltage under specified operating conditions

**3.27**  
**rated power**  
assigned value of power output of a solar cell at rated voltage under specified operating conditions

**3.28**  
**rated voltage**  
assigned value of voltage under specified operating conditions

**3.29**  
**relative spectral response**  
 $S(\lambda)_{rel}$   
spectral response normalized to unity at wavelength of maximum response

NOTE  $S(\lambda)_{rel} = S(\lambda)/S(\lambda)_{max}$

**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****solar cell**

basic photovoltaic device that generates electricity when exposed to sunlight

**3.32****solar constant**

rate of total solar energy at all wavelengths incident on a unit area exposed normally to rays of the sun at one astronomical unit in AM0 conditions

NOTE The average of values is  $1\,367\text{ W}\cdot\text{m}^{-2} \pm 7\text{ W}\cdot\text{m}^{-2}$ .**3.33****solar elevation angle** $\theta$ 

angle between the direct solar beam and the horizontal plane

NOTE This angle is measured in radians.

**3.34****spectral irradiance** $E_{\lambda}$ 

irradiance per unit bandwidth at a particular wavelength

NOTE The units are expressed as  $\text{W}\cdot\text{m}^{-2}\cdot\text{m}^{-6}$ .**3.35****spectral photon irradiance** $E_{p\lambda}$ 

photon flux density at a particular wavelength

NOTE  $E_{p\lambda} = 5,035 \times 10^{14} \lambda \cdot E_{\lambda}$ , where  $\lambda$  is expressed in micrometers.**3.36****spectral irradiance distribution**

spectral irradiance plotted as a function of wavelength

NOTE The units are expressed as  $\text{W}\cdot\text{m}^{-2}\cdot\text{m}^{-6}$ .**3.37****spectral response** $S(\lambda)$ 

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

NOTE The units is  $\text{A}\cdot\text{W}^{-1}$ .**3.38****standard test conditions****STC**at cell temperature of  $25\text{ °C} \pm 1\text{ °C}$  and at one solar constant AM0 irradiance of  $1\,367\text{ W}\cdot\text{m}^{-2}$  as measured with an AM0 standard solar cell using the AM0 reference extraterrestrial solar spectral irradianceNOTE Cell temperature of  $28\text{ °C}$  only applies to 8.4.1.

**3.39**  
**voltage temperature coefficient**

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

NOTE  $\beta$  is expressed in volts per degree Celsius ( $V \cdot ^\circ C^{-1}$ ).

**4 Symbols and abbreviated terms**

AM	air mass
AM0	air mass zero
AU	astronomical unit
$\alpha$	coefficient of current temperature
$\beta$	coefficient of voltage temperature
CAST	China Academy of Space Technology
CNES	French National Space Research Center
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
$I_L$	load current
$I_{Pmax}$	maximum power current
$I_{sc}$	short circuit current
INTA-Spasolab	Instituto Nacional de Tecnica Aeroespacial - Spasolab
$I-V$	current-voltage
JPL	Jet Propulsion Laboratory
NASA-GRC	National Aeronautics and Space Administration – Glenn Research Center
NASDA	National Space Development Agency of Japan
NIP	normal incidence pyrhelimeter
NSBF	National Scientific Balloon Facility in Palestine, Texas
$P_L$	load power
$P_{max}$	maximum power
PTB	Physikalisch-Technische Bundesanstalt
PV	photovoltaic
RTD	platinum resistance thermometers
$S(\lambda)$	spectral response
$S(\lambda)_{rel}$	relative spectral response
STC	standard test conditions
$T_{amb}$	ambient temperature
$T_j$	cell temperature

TC	telecommand
TM	telemetry
$\theta$	solar elevation angle
$V_L$	load voltage
$V_{oc}$	open circuit voltage
$V_{Pmax}$	maximum power voltage
WRC	World Radiation Centre
WRR	World Radiometric Reference

## 5 Measurement principles for space solar cells

### 5.1 Measurement principles

In current practice, the photovoltaic performance of a solar cell is determined by exposing it at a known temperature to stable sunlight or simulated light and tracing its current-voltage characteristic while measuring the magnitude of the incident irradiance.

The measured performance is then corrected to STC or other desired conditions of irradiance and temperature. The corrected power output at the rated voltage and STC is commonly referred to as the rated power.

Since a solar cell has a wavelength-dependent response, its performance is significantly affected by the spectral distribution of the incident radiation, which in extraterrestrial sunlight varies with the location of the sun and earth, season, time of year and time of day, and with a simulator varies with its type and conditions. If the irradiance is measured with a thermopile-type radiometer that is not spectrally selective, the measured conversion efficiencies can vary by several percent because of spectral distribution changes.

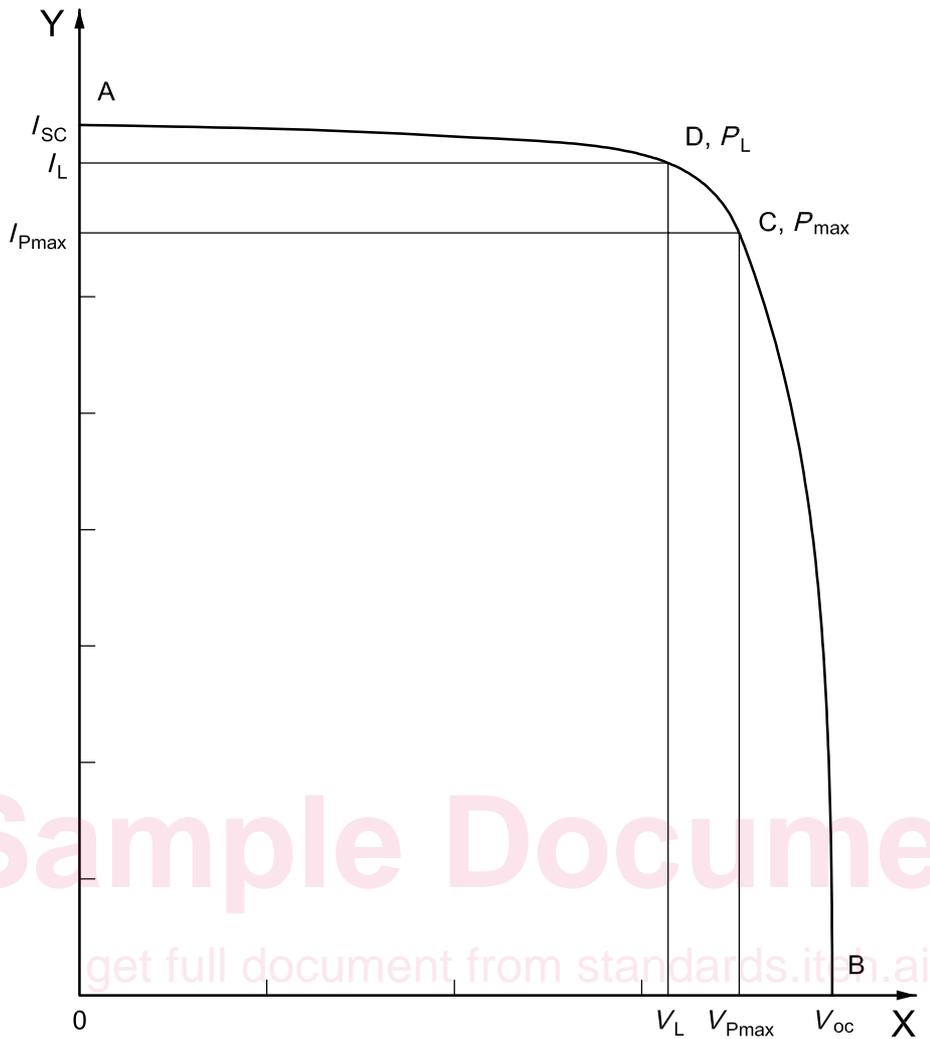
The principles given in this International Standard are designed to reduce such discrepancies by relating the performance rating to a reference extraterrestrial solar spectral irradiance distribution. This is done by measuring the irradiance with an AM0 standard solar cell that has essentially the same relative spectral response as the test specimen and has been calibrated in terms of short-circuit current per unit of irradiance ( $AW^{-1}m^{-2}$ ) with the reference spectral distribution.

If the performance of a solar cell is related to a known spectral irradiance distribution, it is possible for a user or array designer, using the spectral response of the cells, to compute within a reasonable tolerance its performance when exposed to the light of any other known spectral irradiance distribution.

### 5.2 Current-voltage characteristics

See Annex A. One example of an  $I$ - $V$  curve measured at a fixed irradiance and temperature is shown in Figure 1. The current is plotted along the ordinate, the voltage along the abscissa. The electrical characteristics, which may be derived from the  $I$ - $V$  curve are:

- short-circuit current ( $I_{sc}$ ): Point A – the current value where the  $I$ - $V$  curve crosses the current axis at  $V = 0$ ;
- open-circuit voltage ( $V_{oc}$ ): Point B – the voltage value where the  $I$ - $V$  curve crosses the voltage axis at  $I = 0$ ;
- maximum power ( $P_{max}$ ): Point C – the power at the point on the  $I$ - $V$  curve where the product of current and voltage is maximum;
- load current ( $I_L$ ): Point D – the measured current at a specified load voltage  $V_L$ .



X Voltage  
 Y Current  
 Irradiance =  $E$  ( $W \cdot m^{-2}$ )  
 Temperature =  $T$  ( $^{\circ}C$ )

Figure 1 — Example of a current-voltage curve

**6 Basic requirements for AM0 standard solar cell**

**6.1 General**

Clause 6 gives requirements for the classification, selection, packaging, marking, calibration and care of AM0 standard solar cells.

**6.2 Classification**

**6.2.1 Extraterrestrial AM0 standard solar cell**

This is a solar cell whose calibration is based on extraterrestrial AM0 conditions using high altitude balloon or aircraft.

### 6.2.2 Synthetic AM0 standard solar cell

This is a solar cell whose calibration is based on synthetic AM0 conditions using the solar simulator, global sunlight, or direct normal sunlight.

### 6.3 Selection

Solar cells shall be irradiated with one solar constant ( $1\,367\text{ W}\cdot\text{m}^{-2}$  and AM0 spectrum) for 48 h. The cells shall be kept at  $25\text{ °C} \pm 5\text{ °C}$  during the test.

At least two solar cells shall be selected for calibration as AM0 standard solar cells. The spectral response of the selected cells shall be such that errors in performance measurement of the intended test (under extraterrestrial sunlight or specific simulator) caused by spectral response mismatch are less than  $\pm 1\%$ . The spectral mismatch error shall be calculated by the method described in Annex B.

AM0 standard solar cells shall be stable devices, that is their photovoltaic characteristics shall not change from the initial calibration to reevaluation by more than  $1\%$ .

### 6.4 Temperature measurement

Means shall be provided for measuring the AM0 standard solar cell junction temperature to an accuracy of  $\pm 1\text{ °C}$ .

### 6.5 Electrical connections

Any measurement resistor incorporated into the AM0 standard module shall be a high-precision, high-temperature stability resistor with a low value in order to allow the cell to operate at a level close to its short-circuit current. On the other hand, the electrical connections to the AM0 standard solar cell without resistance shall consist of a four-wire contact system (Kelvin probe).

### 6.6 Calibration

Each AM0 standard solar cell shall be calibrated in terms of its short-circuit current at  $25\text{ °C} \pm 1\text{ °C}$  per unit of irradiance with the AM0 reference spectral irradiance ( $\text{A}\cdot\text{W}^{-1}\cdot\text{m}^{-2}$ ).

The standard methods of calibrating both AM0 standard and secondary standard solar cells are described in Clauses 8 and 9. The relative spectral response and the temperature coefficient of each AM0 standard solar cell shall be measured in accordance with Annexes C and D.

### 6.7 Data sheet

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

- a) identification number
- b) type (extraterrestrial AM0 standard or synthetic AM0 standard)
- c) cell manufacturer
- d) manufacturer complete reference of the cell
- e) material type
- f) type of package
- g) calibration organization