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

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Foreword

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International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

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

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.

INTERNATIONAL STANDARD **ISO 15387:2005(E)**

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 × 10^5 Pa.

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

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

where

P = local air pressure in pascals;

P_0 = 1,013 × 10^5, in pascals;

θ = 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 ± 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
α
change of the short-circuit current of a solar cell as a function of the change of cell temperature

NOTE α is expressed in amperes per degree Celsius (A·°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 = $P_{\mathrm{max}}/(V_{\mathrm{oc}} \times I_{\mathrm{sc}})$.

3.12
irradiance
radiant power incident upon unit area of surface

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

3.13
irradiation
integration of irradiance over a specified period of time

NOTE It is expressed in megajoules per square metre ($\mathrm{MJ \cdot m^{-2}}$) 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 $P_{\mathrm{L}} = V_{\mathrm{L}} \times L_{\mathrm{L}}$.

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 $P_{\mathrm{max}} = V_{\mathrm{max}} \times I_{\mathrm{max}}$

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

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

spectral response normalized to unity at wavelength of maximum response

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

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 $\mathrm{W \cdot m^{-2}} \pm 7\ \mathrm{W \cdot m^{-2}}$.

3.33
solar elevation angle
θ
angle between the direct solar beam and the horizontal plane

NOTE This angle is measured in radians.

3.34
spectral irradiance
E_{λ}
irradiance per unit bandwidth at a particular wavelength

NOTE The units are expressed as $\mathrm{W \cdot m^{-2} \cdot m^{-6}}$.

3.35
spectral photon irradiance
$E_{\mathrm{p}\lambda}$
photon flux density at a particular wavelength

NOTE $E_{\mathrm{p}\lambda} = 5{,}035 \times 10^{14}\ \lambda \cdot E_{\lambda}$, where λ is expressed in micrometers.

3.36
spectral irradiance distribution
spectral irradiance plotted as a function of wavelength

NOTE The units are expressed as $\mathrm{W \cdot m^{-2} \cdot m^{-6}}$.

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 $\mathrm{A \cdot W^{-1}}$.

3.38
standard test conditions
STC
at cell temperature of 25 °C ± 1 °C and at one solar constant AM0 irradiance of 1 367 $\mathrm{W \cdot m^{-2}}$ as measured with an AM0 standard solar cell using the AM0 reference extraterrestrial solar spectral irradiance

NOTE Cell temperature of 28 °C only applies to 8.4.1.

3.39
voltage temperature coefficient

β

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

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

4 Symbols and abbreviated terms

AM	air mass
AM0	air mass zero
AU	astronomical unit
α	coefficient of current temperature
β	coefficient of voltage temperature
CAST	China Academy of Space Technology
CNES	French National Space Research Center
ESA	European Space Agency
E_{λ}	spectral irradiance
$E_{\mathrm{p}\lambda}$	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 Aerospacial - 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 pyrheliometer
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
$S(\lambda)_{\mathrm{rel}}$	relative spectral response
STC	standard test conditions
T_{amb}	ambiant temperature
T_{j}	cell temperature

TC	telecommand
TM	telemetry
θ	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

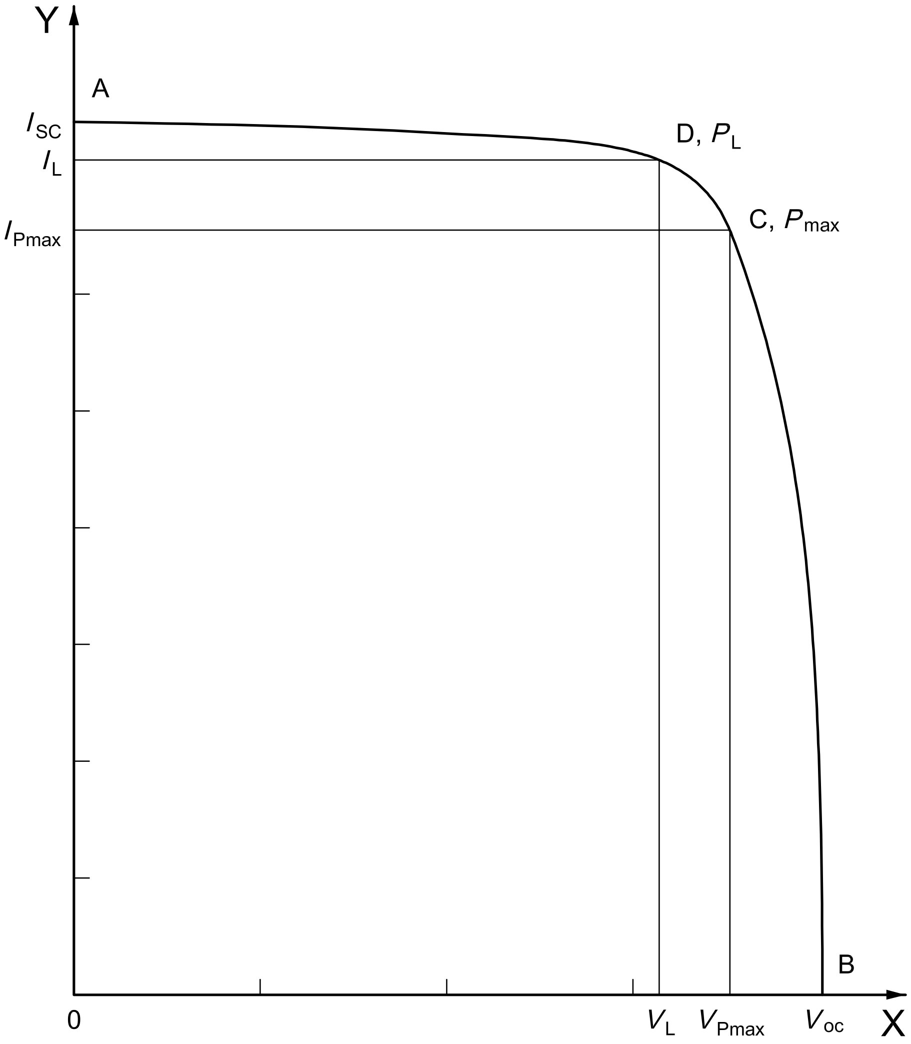
See Annex A. One example of an I-V curve measured at a fixed irradiance and temperature is shown in Figure 1. The current is plotted along the ordinate, the voltage along the abscissa. The electrical characteristics, which may be derived from the I-V curve are:

a) short-circuit current (I_{sc}): Point A – the current value where the I-V curve crosses the current axis at $V = 0$;

b) open-circuit voltage (V_{oc}): Point B – the voltage value where the I-V curve crosses the voltage axis at $I = 0$;

c) 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;

d) load current (I_{L}): Point D – the measured current at a specified load voltage V_{L}.



X Voltage
Y Current
Irradiance = E (W·m^{-2})
Temperature = T (°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 $W \cdot m^{-2}$ and AM0 spectrum) for 48 h. The cells shall be kept at 25 °C ± 5 °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 ± 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 ± 1 °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 °C ± 1 °C per unit of irradiance with the AM0 reference spectral irradiance ($A \cdot W^{-1} \cdot m^{-2}$).

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

h) site and date of calibration

i) method of calibration (refer to standard)

j) radiometer or standard lamp characteristics (where applicable)

k) AM0 standard solar cell identification (where applicable)

l) simulator characteristics (where applicable)

m) type of temperature sensor (where applicable)

n) relative spectral response (where applicable)

o) temperature coefficient of short-circuit current

p) calibration value

q) claimed accuracy

6.8 Marking

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

6.9 Packaging

6.9.1 Measurement in extraterrestrial sunlight

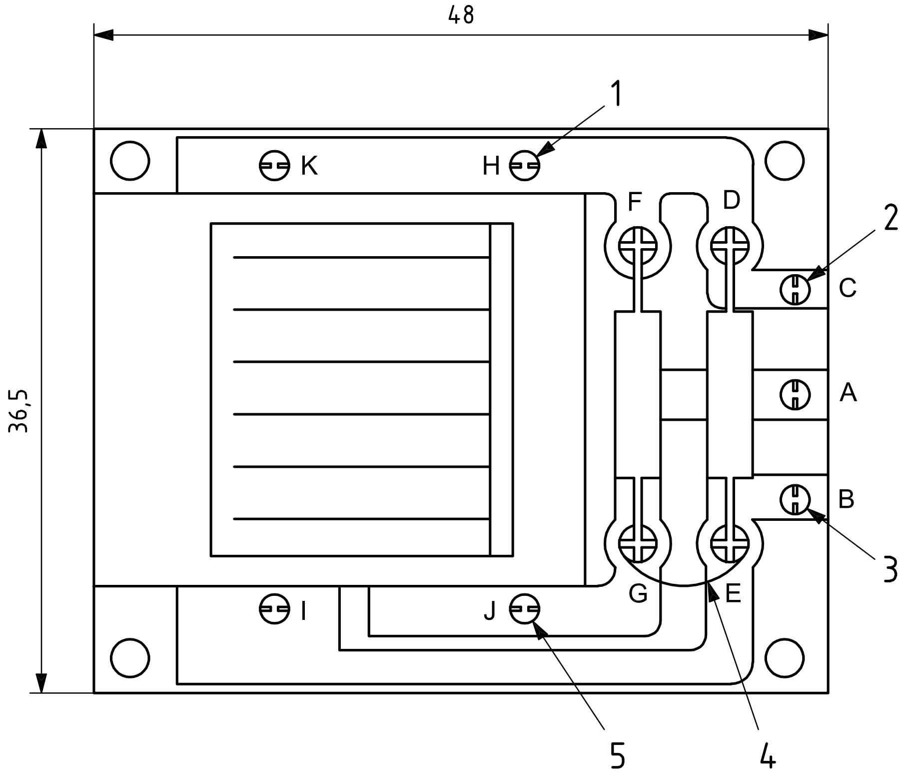
The AM0 standard solar cells used for measurements in extraterrestrial sunlight shall respond to variations in the distribution of the incident radiation in the same way as the test solar cells. Figures 2 and 3 show examples of suitable AM0 standard single cell packages for high altitude balloon flight calibration.

6.9.2 Measurement under simulators

In some simulators, which allow multiple reflections of light to and from the test specimen, the irradiance in the test plane may change depending on whether or not the test specimen is present.

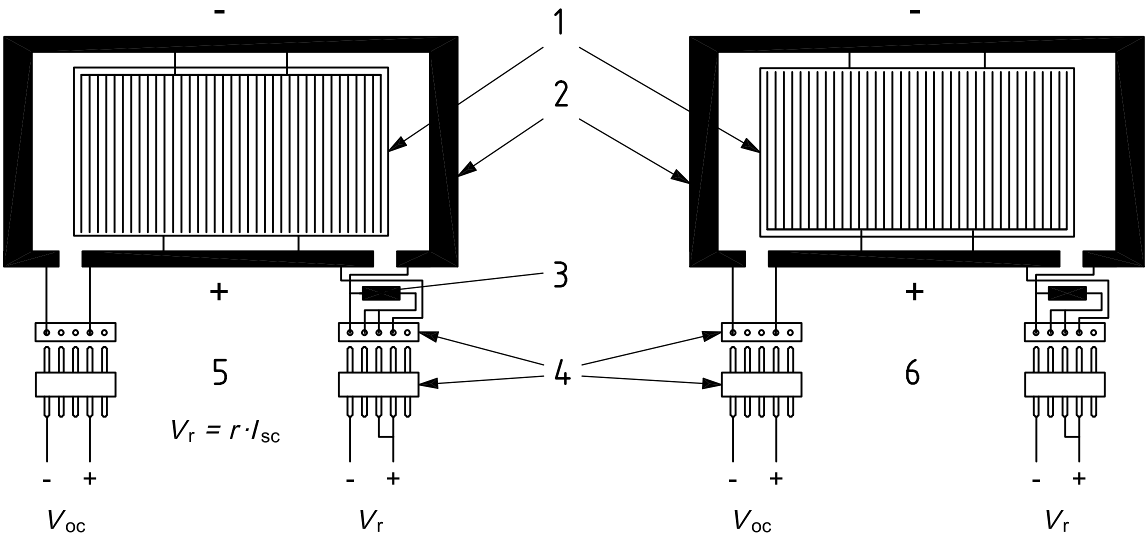
Therefore, in order to measure accurately the irradiance that will be present when the test specimen is in place, the AM0 standard solar cells used in such simulators shall be packaged in the same way as the test specimens, such that the change in irradiance caused by the multiple reflections is the same for both the AM0 standard solar cell and the specimen. AM0 standard solar cells used for measurement in a simulator are designed to render insignificant any error from multi-reflected light may be in the unpackaged state on a temperature controlled block. Alternatively, the requirements given for AM0 standard solar cells designed for use in extraterrestrial sunlight may be followed.

Dimensions in millimetres



Item List	
Item number	**Description**
1	Current terminal (negative)
2	Potential terminal (negative)
3	Potential terminal (positive)
4	Jumper wire
5	Current terminal (positive) (0,1 A rating)

Figure 2 — JPL balloon flight module



Item List	
Item number	**Description**
1	Solar cell
2	Printed circuit
3	Resistor
4	Connectors
5	Si solar cell
6	GaAs solar cell

Figure 3 — CNES balloon flight module

6.9.3 Single cell package

If a single cell package is used, the following recommendations apply.

a) The field of view should be at least 160°.

b) All surfaces in the package within the cell's field of view should be non-reflective, with an absorption of at least 0,95 in the cell's wavelength response band.

c) The material used for bonding the cell to the holder should not be degraded electrically and optically. Its physical characteristics should remain stable over the entire period of intended use.

d) A protective window should be used. If the cell is to be calibrated or used in total sunlight, the space between the window and the cell should be filled with a stable, transparent encapsulant. The reflectance of the encapsulant shall be similar (within 10 %) to that of the window to minimize errors caused by the internal reflection of light at high angles of incidence. The transparency, continuity and adhesion of the encapsulant should not be adversely affected by ultraviolet light and operation temperature.

6.10 Care of AM0 standard solar cells

All standard solar cells shall be kept at temperatures below 50 °C during operation and storage. The standard cells should be kept in the dark during extended storage periods.

The window of a packaged AM0 standard solar cell shall be kept clean and scratch free. Unpackaged AM0 standard solar cells shall be preserved from damage, contamination and degradation. The calibration of AM0 standard solar cells in frequent use shall be cross-checked at intervals of no more than one month by comparing their short-circuit currents under the same irradiance. If there is any change in the current ratios beyond ± 1 %, the cells should be recalibrated. All AM0 standard solar cells shall be reevaluated periodically to check for degradation.

6.11 Calibration of AM0 standard solar cells

The calibration methods of AM0 standard solar cells should be in accordance with Clause 8. The calibration methods and their execution shall have an uncertainty within ± 1 %. The method for determining the uncertainty is given in Annex E.

7 Requirements for AM0 solar spectral irradiance

7.1 General

This International Standard specifies the AM0 reference extraterrestrial solar spectral irradiance.

7.2 AM0 solar spectral irradiance

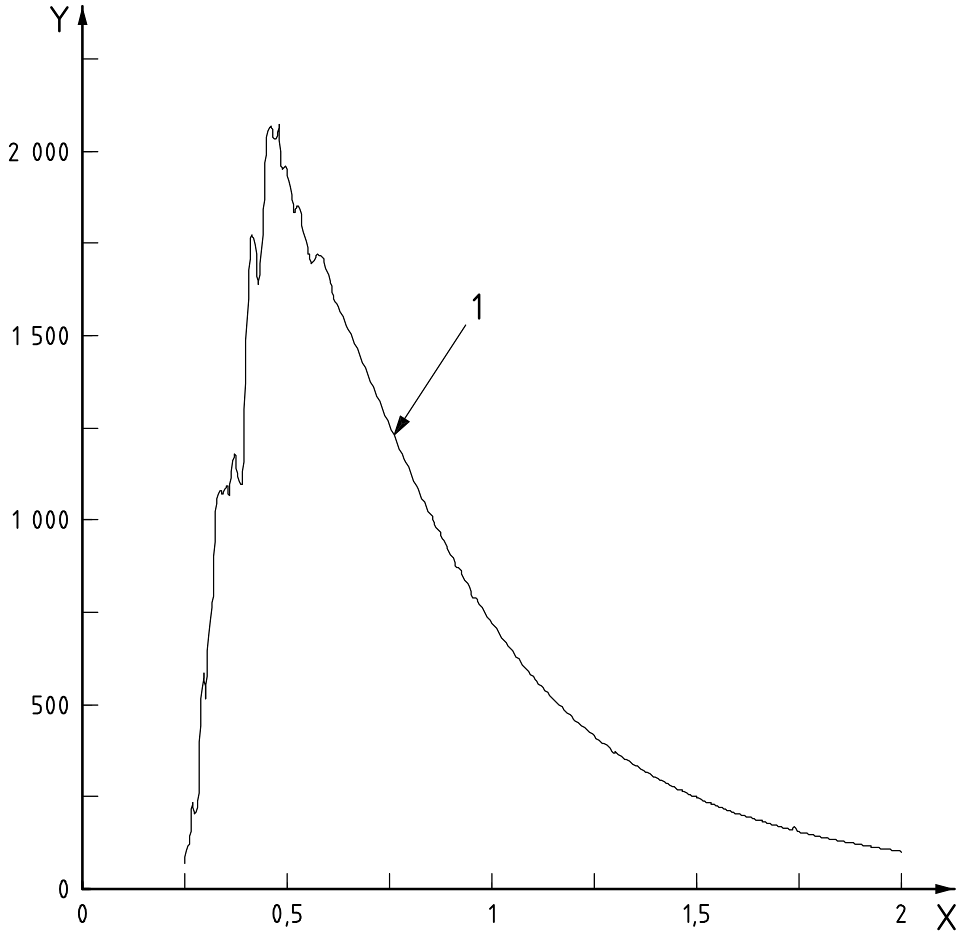
The AM0 reference solar spectral irradiance for the purpose of this International Standard is illustrated in Figure 4. The data from which this curve is drawn are presented in Annex F. This is total sunlight, corresponding to an irradiance of 1 367 W·m^{-2} (solar constant) at AM0, on a plane surface under zero incidence.

8 Calibration for AM0 standard solar cells

8.1 General

This document describes the calibration methods of AM0 standard solar cells. The existing procedures on which these methods are based are claimed by the originators to give results repeatable to within a standard deviation of ± 1 %, if carried out by a competent agency, with no change of equipment.

The calibration methods for AM0 standard solar cell are as follows (see Figure 5).



X Wavelength

Y Solar spectral irradiance (W·m^{-2}·m^{-1})

1 WRC Spectrum

Figure 4 — AM0 solar spectral irradiance (a part of distribution)

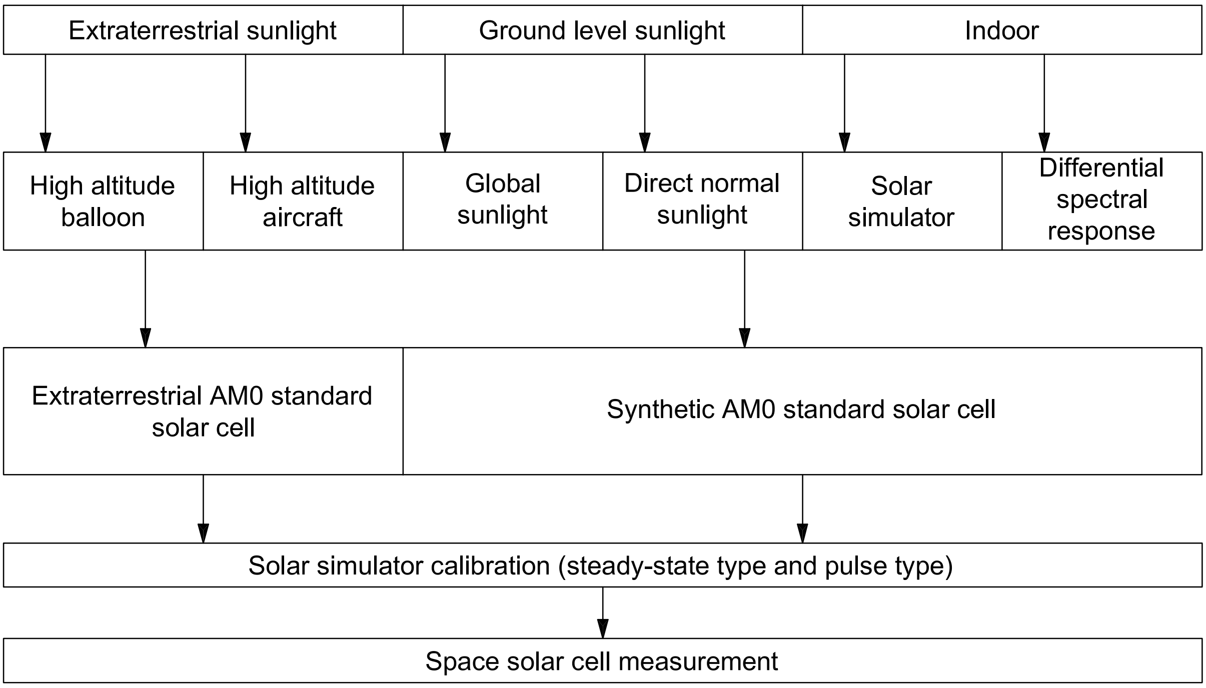


Figure 5 — Calibration methods for (primary) AM0 standard cell

8.2 Extraterrestrial AM0 standard solar cell

a) High altitude balloon flight calibration method

b) High altitude aircraft calibration method

8.3 Synthetic AM0 standard solar cell

a) Global sunlight calibration method

b) Direct normal sunlight calibration method

c) Solar simulator calibration method

d) Differential spectral response calibration method (if applicable)

8.4 Calibration methods of extraterrestrial AM0 standard solar cell

8.4.1 High altitude balloon flight calibration method (JPL)

8.4.1.1 Description

The purpose of the high altitude solar cell calibration program is to produce an extraterrestrial AM0 standard solar cell that can be used for accurately setting solar simulator intensities. The concept is to fly solar cells on a high altitude balloon, to measure their output at altitudes at or above 36 km, to recover the cells and to use them as reference standards. The calibrated standard solar cell is placed in the solar simulator beam, and the beam intensity is adjusted until the standard solar cell reads the same as it read on the balloon. As long as the reference cell has the same spectral response as the cells or panels to be measured, this is a very accurate method of setting the intensity, even though the irradiance of the solar simulator is not an exact match to that of the sun. But as solar cell technology changes, the spectral response of the solar cells changes also, and reference standards that use the new technology must be built and calibrated.

JPL has been flying calibration standards on high altitude balloons since 1963 and continues to organize a calibration balloon flight at least once a year. Up to 39 solar cells can be accommodated on each flight. Full current-voltage curves may be measured on 19 cells, and 30 cells with fixed loads may be measured. The data is corrected to 28 °C and 1 AU ($1{,}496 \times 10^8$ km). The calibrated cells are returned to the participants for use as reference standards.

NOTE Cell temperature of 28 °C only applies to 8.4.1.

8.4.1.2 Principle

The basic principle of the calibration is to measure the short-circuit current (I_{sc}) of each flight cell since I_{sc} is directly proportional to the incident light intensity. In practice, each calibration solar cell is shunted with a load resistor which establishes an operating point near I_{sc}. In addition, the load resistors are chosen so that their output voltage will be less than 100 mV during the flight. The resistors used for loading the cells are highly stable wire wound precision resistors with temperature coefficients of $2 \cdot 10^{-5} \cdot {}^\circ C^{-1}$. The cells connected for full current-voltage curve measurement do not have load resistors. The cells are exposed to direct extraterrestrial sunlight while they are carried on the high altitude balloon. A solar tracker is used to constantly align the solar cells normal to the sun. The tracker assembly is mounted on the apex of the balloon in order to avoid reflections and/or shadowing from the balloon or from any part of the structure hanging below the balloon. If the sun pointing is precise, there are only two corrections that must be made to convert the on-board voltage measurements to the standard condition. One correction is for the earth-sun distance at the time of the flight, and the other is a temperature correction to the standard temperature of 28 °C.

8.4.1.3 Apparatus

See Figure 6.The main components of the balloon flight system are the following.

a) The apex-mounted hoop assembly that contains the experimental package, the data encoder, the recovery system and the camera.

b) The balloon.

c) The lower payload that contains the telemetry, command receiver, and power systems.

The following apparatus is required:

a) Main balloon. This balloon is made of polyethylene film 20 µm thick, has a volume of 98 000 m^3 and weighs 319 kg.

b) Small balloon. This balloon has a volume of 82 m^3 and weighs 4,3 kg.

c) Top payload. The following top payload is mounted to the aluminum hoop assembly.

   1) Solar tracker
   2) Sun angle sensor
   3) Voltage reference (calibration) box
   4) Data acquisition system
   5) Single-frame movie camera
   6) Clock
   7) Descent parachute
   8) Battery power supply for the tracker and data acquisition system
   9) Tracking beacon

d) Bottom payload. The bottom payload is furnished by the National Scientific Balloon Facility (NSBF) and consists of the following.

    1) Battery power supply

    2) Ballast module for balloon altitude control

    3) An electronics module known as the Consolidated Instrument Package (CIP)

    4) GPS receivers

    5) Transponder

    6) Descent parachute

e) Solar cell modules mounted on the tracker solar panel.

f) Ground support equipment is furnished by the NSBF and consists of the following.

    1) Telemetry receiving and recording system

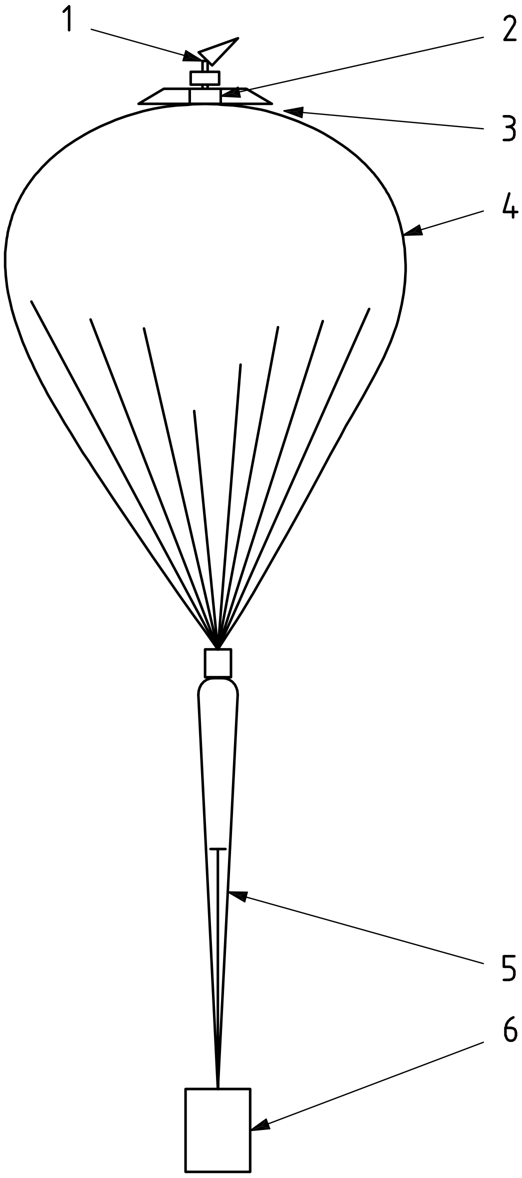
    2) GPS receiver

    3) Computer systems for monitoring balloon position, altitude and status

    4) Launch vehicles

    5) Chase and recovery vehicles

    6) Airplane for tracking, chase and recovery



Item List	
Item number	**Description**
1	Solar panel
2	Solar tracker
3	Hoop assembly and parachute
4	Balloons
5	Bottom parachute
6	Instrument package

Figure 6 — JPL high altitude balloon flight calibration

8.4.1.4 Environmental conditions

The National Scientific Balloon Facility (NSBF) was established in 1963 at Palestine, Texas. The Physical Science Laboratory (PSL) of New Mexico State University operates this facility under the sponsorship of the National Aeronautics and Space Administration (NASA). This location was chosen because it has favourable weather conditions for balloon launching and a large number of clear days with light surface winds. The high altitude winds in this part of the country take the balloons over sparsely populated areas so the descending payloads are unlikely to cause damage to people or property.

The JPL calibration flights have been flown from the Palestine facility since 1973. The flights are scheduled to fly in the June-to-September time period since the sun is high in the sky at that time of year and the sunlight passes through a minimum depth of atmosphere before reaching the solar cell modules. In order to maintain a minimum amount of atmosphere between the sun and the solar cells, the calibrations are carried out at altitude higher than 35 km.

8.4.1.5 Test procedure

Before the flight, the data acquisition system is calibrated by placing a sequence of input voltages into the appropriate input terminals of the DAQ and measuring the corresponding output (in both voltage and data word). A least-squares fit to the measurements is calculated to establish the gain and offset of the DAQ amplifier. This procedure is performed separately for (1) the fixed-load cell amplifier, (2) the voltage amplifier used in measuring current-voltage characteristics and (3) the current amplifier used in measuring the current-voltage characteristics.

The cell temperatures during the flight are measured by reading the resistance of several platinum resistance thermometers (RTDs) embedded in several of the light cell modules. A calibration of the amplifiers used to measure these RTDs is also performed before the flight.

The calibrations described above are performed at room temperature. The temperature stability of the DAQs is measured before flight by placing the DAQs in a temperature controlled oven.

An environmental test of the entire solar cell tracking and data acquisition system is performed before each flight. In this test, the solar panel is fully populated with modules for the flight. The system is placed in a thermal vacuum chamber and powered on. The chamber is evacuated to a pressure corresponding to the expected float altitude of the flight (at 36,6 km the air pressure is 500 Pa). The operation of the DAQs is monitored at temperatures between − 50 °C and + 50 °C. During this time, the operation of the tracker is monitored to assure that it is not adversely affected by temperature.

During the flight, the data is telemetered to the ground station at the NSBF. The solar cell calibration data is sent to a computer dedicated to the real-time display and storage of the solar cell data. Data is accumulated for at least 30 m within 1 h of local solar noon.

At the end of the flight, the solar tracker assembly is separated from the balloon system and allowed to descend by parachute.

Computer analysis of the stored data is performed after the flight. The analysis program corrects the fixed-load cell data for temperature and sun-earth distance according to the following formula:

$$V_{28,1} = V_{\mathrm{T,R}}(R^2) - A \cdot T(T - 28)$$

where

$V_{\mathrm{T,R}}$ is the measured module output voltage at temperature T and distance R;

R is the sun-earth distance (AU);

A is the module output temperature coefficient; and

T is the module temperature (°C).

A slightly different procedure is used for the cells producing current-voltage curves. The correction shown above is made for all measured cell current values, using temperature coefficients (A) appropriate for I_{sc}. The voltages are corrected, utilizing temperature coefficients appropriate for V_{oc}. This correction used the above formula also, but the factor for sun-earth distance is not used. The voltage correction is applied to all measured cell voltage values.

8.4.2 High altitude balloon flight calibration method (CNES method)

8.4.2.1 Description

Since 1975, CNES (French National Space Research Centre) has been involved in the calibration of space solar cells by producing AM0 standard solar cells. Calibrations are performed on board stratospheric balloons flying at high altitudes (36 ± 2 km) where the solar spectral irradiance is very close to AM0. The cells calibrated in this way can subsequently be used as standard solar cell in various laboratory tasks for solar cell characterization by sun simulators. A standard solar cell must be used to adjust and measure the simulated illumination energy. The spectral response of this cell shall be as close as possible to that of the specimen to be measured using the simulator. CNES is the only laboratory in Europe carrying out calibration of this type above the atmosphere, with a flight planned every year.

Size increases, changes in solar cell technology (GaAs/Ge, tandem, tri-junction, etc.) and the impossibility of carrying out tests on the ground led to modification of the electronics of the 1996 flight, thus preparing tomorrow's technologies. This now allows measurement with high accuracy the $I = \mathrm{f}(V)$ curves for 28 modules, at temperatures between –20 °C and 30 °C and with a programmed temperature step (1 °C to 10 °C).

8.4.2.2 Principle

An electronics payload is carried on-board the balloon's gondola, allowing the characteristic current-voltage relationship $I = \mathrm{f}(V)$ to be recorded as a function of temperature, under real illumination AM0, with corrections made for the following:

K_{n}	Residual atmosphere at the balloon's altitude (see 8.4.2.8),
K_{s}	Variation of illumination caused by the varying earth-sun distance over the year (see 8.4.2.8).

Two supply voltages are connected to the cell during the measurements. One is negative and fixed, the other is positive and can be programmed from 0 to 5 V with a resolution of 1,22 mV. The direct characteristic is obtained by polarizing the cell with a programmed supply voltage. The cell voltage decreases from V_{oc} (open circuit voltage) to 0 while I_{c} (cell current) increases from 0 to I_{sc} (short-circuit current). I_{c} and V_{c} (cell voltage) are measured after each programmed supply voltage. Up to 92 values of I_{c} and V_{c} can be measured for each curve. Each cell may be represented by the equivalent diagram shown in Figure 7, with the following notation:

V_{ca}	Backward feed voltage
R_{L}	Load resistance
V_{p}	Polarization voltage
V_{r}	Resistance voltage
V_{c}	Cell voltage

The solar cell unit contains a high precision (0,1 %), high temperature stability (2×10^{-5}) resistor, with a low resistance in order to allow the cell to operate at close to its short-circuit current. The in-flight measurement is written:

$$V_{\mathrm{p}} = V_{\mathrm{r}} - V_{\mathrm{c}} + V_{\mathrm{ca}} \quad \text{(see 8.4.2.8).}$$

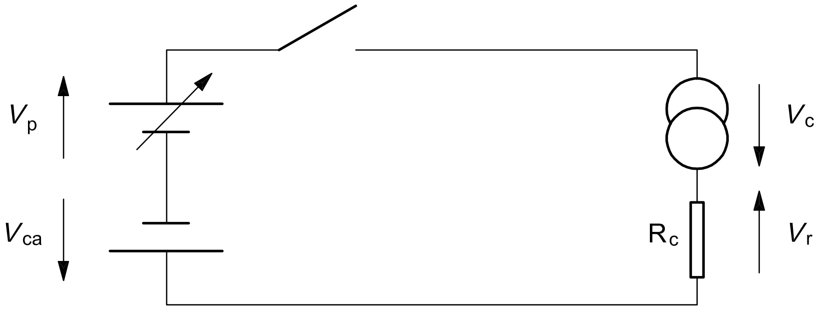


Figure 7 — Electrical diagram

8.4.2.3 Test procedure

8.4.2.3.1 Ground measurements

a) Validation of electrical parameters under permanent simulator or flasher illumination

b) Calibration of thermocouple and other detectors with respect to temperature

c) Laboratory determination of V_oc and V_r = f (T) by using the flight electronics system

d) Determination of the spectral response of the cells

8.4.2.3.2 Flight measurements

The characteristic curves are obtained by (see Figure 8):

a) Determining $V_\mathrm{p0} = V_\mathrm{ca} - V_\mathrm{oc}$

b) Determining $V_\mathrm{pf} = V_\mathrm{ca} + V_\mathrm{r\,max}$

c) Calculating the voltage step of the variable power supply: $\text{step} = \dfrac{V_\mathrm{pf} - V_\mathrm{p0}}{92}$

d) Determining the characteristic curve by varying the voltage between V_pf and V_p0 in 92 points.

e) Measuring the initial and final temperatures:

where

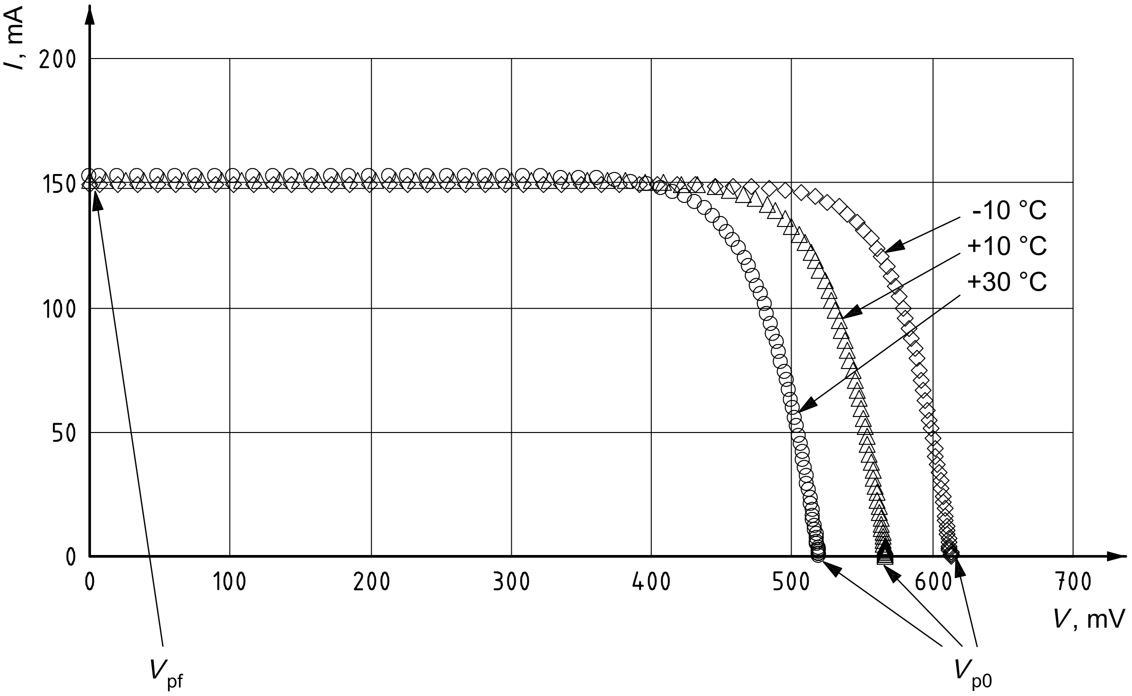
V_p0 is the initial polarization voltage;

V_pf is the final polarization voltage; and

V_oc is the open circuit voltage.

All measurements are recorded in E^{2}EPROM memory. Flight data storage is also available. CNES can provide either unprocessed or mathematically processed data. All processing is carried out at the CNES computing centre in Toulouse, France.

NOTE $V_\mathrm{r\,max}$ is set to 2 volts; it depends on the measuring resistance and on the characteristic I = f(V) of the solar cell.



New payload solar cell Si BSR 2 × 4 cm^2 at three temperatures: − 10 °C, + 10 °C, + 30 °C

Figure 8 — Example of current-voltage curve relative to payload solar cell at three temperatures

8.4.2.4 Accuracy

The characteristic $I = f(V)$ curve is measured to within ± 0,5 %.

After calibrating the measurement system, the temperature measurements are accurate to within ± 0,5 °C.

The measurement accuracy of the spectral response (λ, T) is TBD.

8.4.2.5 Supply

Each calibrated cell consists of a casing fitted with a five-pin connector and is supplied with the following:

- a spectral response curve;
- a curve giving the variation of the calibration value with temperature;

NOTE This curve usually approximates a straight line over the temperature range in question.

- the curve $I = f(V)$ for three temperatures including $T = 25$ °C;
- values for V_r, V_{oc}, dV_r/dT and dV_{oc}/dT; and
- flight date, altitude and flight time.

8.4.2.6 Apparatus

See Figure 9. The on-board system for the stratospheric balloon flight is made up of three parts:

- a scientific gondola
- a telemetry and telecommand unit
- a tracking gondola

The following apparatus is required:

- Launch center: Aire-sur-l'Adour and Gap, France
- Carrier balloon: 100 000 m^3
- Auxiliary balloon
- Recovery parachute
- Two wire link cable
- Tracking gondola
- Second two wire link long enough to avoid shadows on the scientific gondola
- Scientific gondola carrying telemetry and telecommand unit
- Solar cell module with resistor

8.4.2.7 Environmental conditions

The calibration shall be carried out at an altitude of 36 km ± 2 km and the balloon altitude shall be maintained within the operational limits required by the test apparatus.

The CNES calibration flights have flown from Aire-sur-l'Adour or Gap (in France) facilities since 1975. The flights are scheduled between June and September, since the sun is high in the sky at this time of year so that the sunlight passes through a minimal thickness of the atmosphere before reaching the solar modules.

8.4.2.8 Mathematical processing

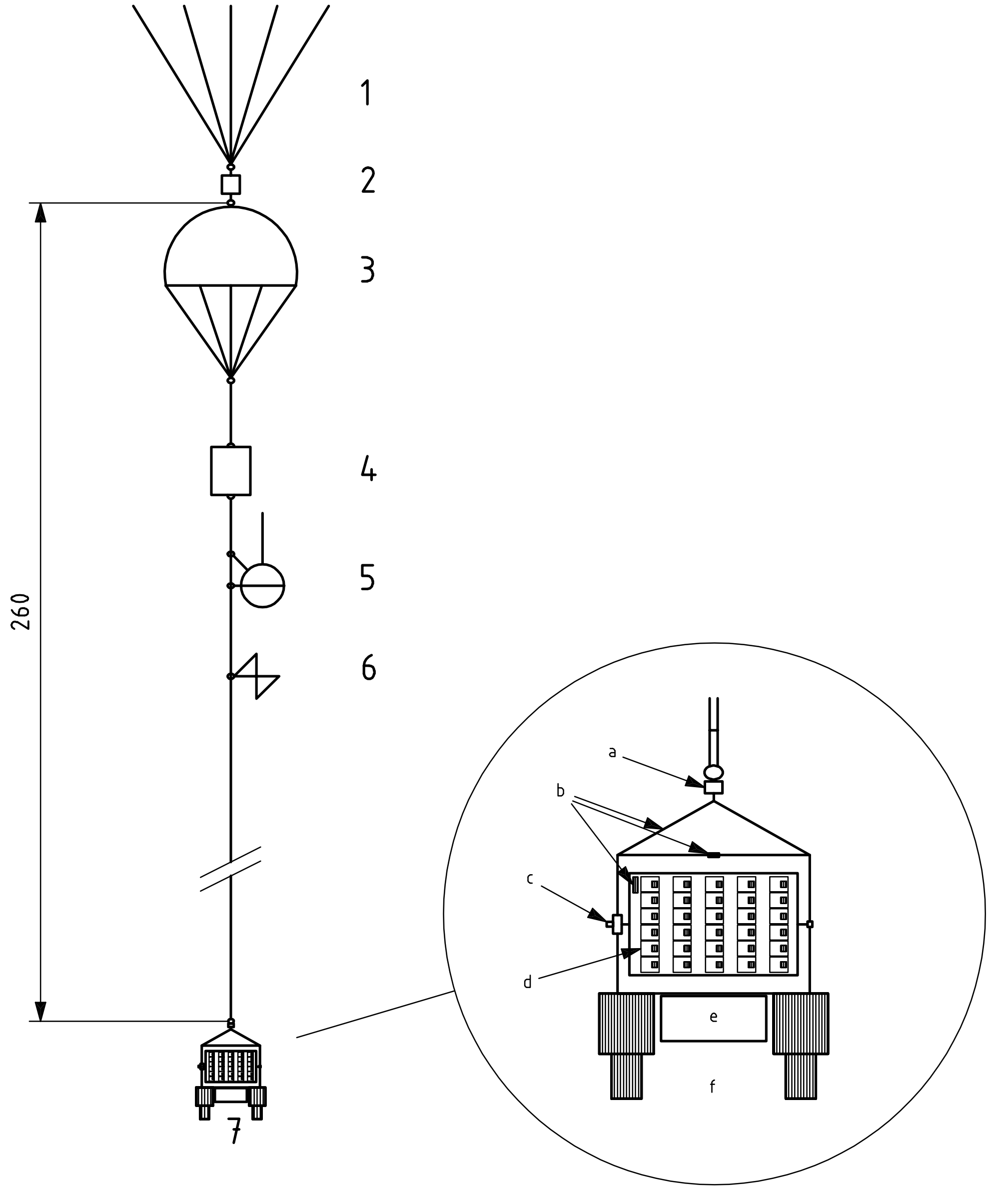
8.4.2.8.1 Determination of altitude h versus pressure.

$$h(p) = \mathrm{a} + \mathrm{b} - \ln p + \mathrm{c}\,(\ln p)^2 + \mathrm{d}\,(\ln p)^3$$

where

a, b, c, and d	are constants;
p	is the ambient pressure.

Dimensions in metres



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Balloon	7a	Motor
2	Pyrotechnic separator	7b	Structure
3	Parachute	7c	Sun sensor motor
4	Localization gondola	7d	Solar cells
5	Beacon	7e	TM/TC gondola
6	Radar reflector	7f	Shock absorber
7	Scientific and TM/TC gondola		

Figure 9 — CNES high altitude balloon calibration

8.4.2.8.2 $\Delta T(t)$ is the time equation approximated by the seventh order expression:

$$\Delta T(t) = \mathrm{b}_0 + \mathrm{b}_1 t + \mathrm{b}_2 t^2 + \ldots + \mathrm{b}_7 t^7$$

where

b_0, b_1, etc. are constants,

t is the day of the year;

$\Delta T(t)$ is given in decimal minutes.

8.4.2.8.3 Determination of true solar time (T_{SV}) from the following equation:

$$T_{\mathrm{SV}} = T_{\mathrm{U}} + \Delta T + \frac{4\,L}{60}$$

where

L is the longitude counted positively eastwards;

T_{U} is the universal time

8.4.2.8.4 Variation in solar declination during the year $\delta(t)$; a satisfactory approximation is obtained using the expression:

$$\delta(t) = -23{,}45 \cos[360/365(t - 9{,}25)]$$

where

t is the day of the year;

$\delta(t)$ is in decimal degrees.

8.4.2.8.5 Calculation of the sun's zenith distance by using:

$$\cos \Psi = \sin l \cdot \sin\left[\delta(t)\right] - \cos l - \cos\left[\delta(t)\right] \cdot \cos(15\, T_{\mathrm{SV}})$$

where

Ψ is the angle between the vertical and the sun's direction and

l is the latitude.

8.4.2.8.6 Solar spectral irradiance outside the atmosphere $S_0\,(\lambda)$:

See Annex F for necessary data. The solar constant is 1 367 W·m^{-2}.

8.4.2.8.7 Determination of the solar spectral irradiance $S(\lambda)$ at the balloon's altitude at the time of measurement:

$$S(\lambda) = S_0(\lambda) \times \exp\,[\mathrm{CAR}(h, \lambda) \times \frac{1}{\cos \Psi}]$$

where CAR(h, λ) is the coefficient of residual atmospheric absorption.

NOTE Values are given in the *Handbook of Geophysics* for 22 wavelengths and 51 altitudes. Values are read off against flight altitude by using linear interpolation.

8.4.2.8.8 Determination of the correction factor for each solar cell:

$$K_{\mathrm{n}}(t)=\frac{\int_0^{\infty} R_{\mathrm{Sn}}(\lambda)\times S_0(\lambda)\mathrm{d}\lambda}{\int_0^{\infty} R_{\mathrm{Sn}}(\lambda)\times S(\lambda)\mathrm{d}\lambda}$$

where

t	is the day of the year
$R_{\mathrm{S}}(\lambda)$	is the spectral response of solar cell n (mA/mW·cm^2)
$S_0(\lambda)$	is the solar spectral irradiance AM0 (W/m^2·µm)
$S(\lambda)$	is the solar spectral irradiance at the balloon altitude (W/m^2·µm)
n	is the number of solar cells to be calibrated, n = 1 to 28

8.4.2.8.9 Determination of K_{A}, which is the correction factor to be applied to the voltage measurements, function of the temperature of the on-board measurement amplifier.

8.4.2.8.10 Laboratory determination before the flight of the temperature of each of the solar cells as a function of its open circuit voltage:

$$T_{\mathrm{n}}=\mathrm{a}_{\mathrm{n}}V_{\mathrm{oc}}^2+\mathrm{c}_{\mathrm{n}}V_{\mathrm{oc}}-\mathrm{d}_{\mathrm{n}}$$

where a_{n}, c_{n} and d_{n} are constants.

This function is determined in the laboratory for each solar cell by measuring V_{oc} (amplified by the on-board measurement system) for different temperatures.

8.4.2.8.11 $K_{\mathrm{s}}(t)$ is the illumination correction factor allowing for the variation in the earth-sun distance over the year and is given by:

$$K_{\mathrm{s}}(t)=1{,}001\,7-0{,}338\cos(t-7)$$

where t is the day of the year.

8.4.2.8.12 Determination for each solar cell of the calibration value V_{r} corresponding to a constant solar illumination at a temperature:

$$V_{\mathrm{r,n}}(i)=K_{\mathrm{s}}(t)\times K_{\mathrm{n}}(t)\times K_{\mathrm{A}}\times V_{\mathrm{n}}(i)$$

where

$V_{\mathrm{r,n}}(i)$ is the voltage measured at the terminals of a load resistor for the characteristic I = f(V) curve, i varying over 92 measuring points

$$V_{\mathrm{r,n}}=K_{\mathrm{s}}\times K_{\mathrm{n}}\times K_{\mathrm{A}}\times V_{\mathrm{n}}$$

where V_{n} is the measured voltage (voltage across built-in resistor) for cell n.

After the frames have all been processed, the program plots the curves of $V_{\mathrm{r,sc}}$ = f(T), I_{sc} = f(T) et V_{oc} = f(T) and calculates d$V_{\mathrm{r,sc}}$/dT and dV_{oc}/dT for T = 25 °C.

8.4.3 High altitude aircraft calibration method (NASA-GRC)

8.4.3.1 Principle

The short-circuit current (I_{SC}) is obtained by exposing the solar cells directly to the sun at high altitude. Data is obtained over a range of altitudes. I_{SC} is plotted versus AM, then the I_{SC} at AM0 is obtained.

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.

8.4.3.2 Apparatus

The following apparatus is required.

a) An aircraft capable of flight to 15,4 km altitude and descent controlled in roll, pitch and yaw axes to 1°.

b) A 5:1 or better collimating tube mounted in the aircraft with an external shutter to protect the cells during takeoff, landing and low altitude flight.

c) A computer system for control and data storage.

d) A calibrated, high-sensitivity absolute-pressure transducer.

e) A calibrated, cockpit-mounted sunlight.

f) An absolute cavity radiometer, calibrated to a primary standard conforming to World Radiation Centre standards

8.4.3.3 Environmental conditions

The calibration must be carried out in the region of the atmosphere designated as the stratosphere. The time of year that will provide the largest possible sun elevation angle shall be selected. Cell temperature shall be 25 °C °± 1 °C during calibration.

8.4.3.4 Test procedure

a) Mount the test cells on the temperature controlled plate which acts as the end cap of the collimating tube. Ensure proper ohmic contacts with a transistor curve tracer.

b) Select the proper load resistor for each cell. The resistor shall be sized so that the voltage drop across the cell at one sun illumination (AM0) shall be less than or equal to 20 mV. A wire-wound, low inductance precision resistor with an accuracy rating of at worst ± 0,1 % shall be used.

c) Determine whether the proper atmospheric conditions have been met for the flight. The upper atmosphere data must be that obtained at 12:00 GMT on the day of the calibration flight from at least three relevant locations. Check with aircraft operations as to the suitability of surface weather conditions for safe flight operations.

d) Calculate proper tube angle setting of the data from the current Astronomical Almanac.

e) Input cell identification data, load resistor values, sun and tube angle data, true geocentric distance value and temperature control data into the control computer software.

f) Adjust the collimating tube and pilot sunlight to their proper angles.

g) Mount the test plate to the end of the collimating tube in the aircraft. Change load resistors, if necessary. Update software in the on-board computer. Test entire aircraft system, including computer software and hardware, the data acquisition system, external shutter, temperature control, pilot interface and pressure transducer.

h) After the flight, remove the cell mounting plate from the collimating tube and the calibration data from the computer. Visually inspect all aircraft calibration equipment.

i) Plot the logarithm of I_{sc} versus the air mass number. Correct for the geocentric distance and ozone absorption, and extrapolate plot to air mass value of zero to obtain the cell calibration value.

8.5 Calibration methods of synthetic AM0 standard solar cell

8.5.1 Global sunlight calibration method (INTA-Spasolab)

8.5.1.1 Description

Two different methods are commonly used for primary standard calibration: the "direct" method and the "global" method. In the direct method, a normal incidence pyrheliometer and the solar cell, placed at the bottom of a collimator tube, are kept pointing at the sun while measurements of short-circuit current and solar irradiation are made. In the global method, the cell (uncollimated), and pyranometer are placed on a horizontal surface, and simultaneous readings of irradiance and short-circuit current are taken in global sunlight.

It is claimed that because some of the shorter wavelengths lost in atmospheric scattering are recovered as diffuse blue radiation from the sky (M.W. Walkden, 1967), the global spectral distribution is closer to AM0 than the direct one. Besides, the global method requiring neither collimation nor accurate orientation is easier to implement. The global method involves the following steps.

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

b) Mount the cell on a temperature controlled block coplanar with a horizontal pyranometer, allowing an unobstructed view over a solid angle of 2π steradians.

c) Measure the short circuit current of the cell in global sunlight.

d) Measure the global irradiance at the same time as the short-circuit current.

e) Measure the relative spectral irradiance distribution on the global sunlight at the same time as the other measurements.

f) Compute the calibration value.

g) Take the average of at least three calibrations on three different days.

8.5.1.2 Method of computation

The method of computation is:

$$I_{\mathrm{sr}} = \int S_{\lambda} E_{\mathrm{s}\lambda} \mathrm{d}\lambda \tag{1}$$

$$I_{\mathrm{sg}} = \int S_{\lambda} E_{\mathrm{g}\lambda} \mathrm{d}\lambda \tag{2}$$

$$E_{\mathrm{glob}} = \int E_{\mathrm{g}\lambda} \mathrm{d}\lambda = \frac{1}{K_2} \int K_2 E_{\mathrm{g}\lambda} \mathrm{d}\lambda$$

or

$$I_{\mathrm{sg}} = \frac{1}{K_2} \int S_{\lambda} K_2 E_{\mathrm{g}\lambda} \mathrm{d}\lambda = \frac{E_{\mathrm{glob}}}{\int K_2 E_{\mathrm{g}\lambda} \mathrm{d}\lambda} \times \int S_{\lambda} K_2 E_{\mathrm{g}\lambda} \mathrm{d}\lambda \tag{3}$$

Dividing Equation (1) by Equation (3) results in:

$$I_{\text{sr}} = I_{\text{sg}} \frac{\int K_2 E_{\text{g}\lambda} \mathrm{d}\lambda}{E_{\text{glob}}} \times \frac{\int S_\lambda E_{\text{s}\lambda} \mathrm{d}\lambda}{\int S_\lambda K_2 E_{\text{g}\lambda} \mathrm{d}\lambda}$$

Because S_λ appears in both numerator and denominator, relative values of spectral response embodying the same constant may be used. Thus,

$$I_{\text{sr}} = I_{\text{sg}} \frac{\int K_2 E_{\text{g}\lambda} \mathrm{d}\lambda}{E_{\text{glob}}} \times \frac{\int (K_1 S_\lambda) E_{\text{s}\lambda} \mathrm{d}\lambda}{\int (K_1 S_\lambda)(K_2 E_{\text{g}\lambda}) \mathrm{d}\lambda}$$

The calibration value may be computed from the tabulated values of $E_{\text{g}\lambda}$ and measured values of I_{sg}, $K_1 S_\lambda$, $K_2 E_{\text{g}\lambda}$, and E_{glob}.

8.5.1.3 Environmental conditions

The global method is simple and free from collimator alignment and field of view errors, but it requires a good test site since the main requirements of the calibration site are:

a) Calibration site located to give an unobstructed view of the sky over a full hemisphere, well away from any large buildings and free of atmospheric pollution.

b) Global irradiance on a horizontal plane not be less than 800 W·m^{-2}.

c) Diffuse irradiance less than 25 % of global irradiance.

d) Solar elevation not be less than 54° in order to minimize the cosine law errors on the spectroradiometer and pyranometer.

e) Solar radiation sufficiently stable to allow the spectral irradiance distribution to be measured.

f) Prevailing good weather so that measurements can be taken on three suitable days without undue delay.

8.5.1.4 Equipment necessary to carry out the calibration

a) Spectroradiometer to measure the relative spectral irradiance at wavelength λ of the global sunlight ($K_2 E_{\text{g}\lambda}$). It shall be able to measure inside of the wavelength range from 200 nm to 2 500 nm.

b) Pyranometer to measure the irradiance of the global sunlight ($E_{\text{glob.}}$).

c) Standard holder unit on temperature controlled block placed coplanar with a horizontal pyranometer and the spectroradiometer allowing the cell an unobstructed view over a solid angle of 2π steradians. The cell electrical connections should be done using a four-point solar cell load circuit.

d) Data acquisition system consisting of a voltmeter, ammeter, and thermometer to record current, voltage, and temperature.

8.5.2 Direct sunlight calibration method (CAST)

8.5.2.1 Description

In this method, only the direct normal component of the ground sunlight is used. The restrictions on the location and weather condition are greatly reduced.

8.5.2.2 Principle

The AM0 short-circuit current of the reference solar cell can be obtained from the following equation:

$$I_{0\text{sc}} = \frac{I_{\text{sc}} \int E_\lambda \mathrm{d}\lambda \int E_{\text{R}\lambda} S_{\text{r}\lambda} \mathrm{d}\lambda}{E \int E_\lambda S_{\text{r}\lambda} \mathrm{d}\lambda} \tag{4}$$

where

$I_{0\text{sc}}$ is the short circuit current of the reference solar cell in AM0 standard sunlight;

I_{sc} is the short circuit current output of the cell in direct normal terrestrial sunlight;

E_λ is the relative spectral irradiance at wavelength λ of the direct sunlight in which the short circuit current was measured;

E is the measured total irradiance of direct sunlight;

$E_{\text{R}\lambda}$ is the absolute spectral irradiance at wavelength l of AM0 standard sunlight;

$S_{\text{r}\lambda}$ is the relative spectral response of the reference cell at wavelength λ.

8.5.2.3 Environmental conditions

The calibration shall be carried out in natural sunlight under the following conditions:

a) Clear, blue sky, sky with no observable cloud formation within a 15° half-angle cone surrounding the sun.

b) Irradiance more than 800 W·m^{-2} as measured with a pyrheliometer.

c) Atmospheric condition sufficiently stable so that the variations in the reference cell short-circuit current are less than ± 0,5 % during any 30-second measurement period.

d) The ratio of uncollimated to collimated short-circuit current of less than 0,2 (e.g. ratio of diffuse to direct less than 20 %).

8.5.2.4 Test procedure

a) At the calibration site, mount the reference cell on its holder, which is mounted on a tracker with a collimator tube.

b) Ensure that the reference cell temperature is 25 °C ± 1 °C.

c) Verify that the collimation ratio is less than 1,2.

d) Ensure that the pyrheliometer and all the collimator tubes for reference cell and spectroradiometer are parallel to the direct sunlight beam in 0,2° solid angle.

e) Measure the direct irradiance with a pyrheliometer.

f) Simultaneously record the relative spectral irradiance with a spectroradiometer and the short-circuit current of the reference cell.

g) Measure the relative spectral response of the reference cell in laboratory.

h) Compute the calibration value according to Equation (4).

i) Take the average of at least three calibrations on three different days.

8.5.2.5 Equipment

The equipment necessary to carry out the calibration is as follows:

a) Spectroradiometer to measure the relative spectral irradiance of the direct terrestrial sunlight. It must be able to measure inside of wavelength range from 300 nm to 2 500 nm.

b) Pyrheliometer to measure the absolute irradiance of the direct terrestrial sunlight.

c) Collimator tubes for the reference cell and spectroradiometer, which have the same field of view as that of the pyrheliometer.

8.5.3 Solar simulator calibration method (NASDA)

8.5.3.1 General

This calibration method applies to the single junction solar cells only.

8.5.3.2 Principle

The calibration value is calculated from

a) The relative spectral response of the solar cell,

b) The short-circuit current of the solar cell under simulated sunlight,

c) The spectral irradiance of the solar simulator, and

d) The AM0 solar spectral irradiance.

8.5.3.3 Apparatus (see Figure 10)

See Figure 10.The following apparatus is required.

a) Solar simulator with the following characteristics:

   - stable steady-state operation,
   - stabilized power supply, regulated by a feed-back circuit with a light monitor,
   - irradiance control system which changes the irradiance widely,
   - temperature-controlled sample table which always mounts the AM0 standard solar cells at the same position by two knock pins corresponding to the encapsulated standard module or the cell holder,
   - irradiance non-uniformity checker,
   - intensity variation checker which compensates the fluctuation of Isc of solar cells,
   - temperature-control equipment for solar cells, and
   - computer system for data acquisition and data processing (I-V curve).

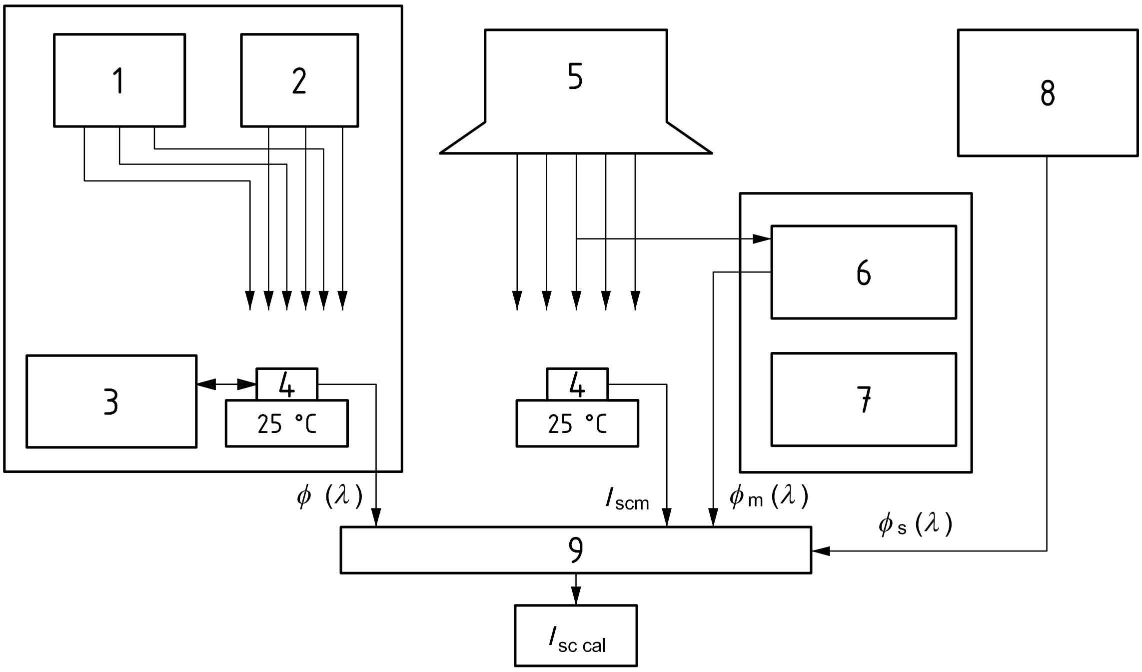
b) Spectroradiometer with the following characteristics:

   - high-resolution spectroradiometer with a double monochromator covering a wide wavelength,
   - fully computer-aided measurement and data processing,
   - standard halogen lamp (traceable to national standard),

- temperature controllers for detectors,
- computer system for measurement and data processing,
- regulated power supply for the standard lamp, and
- digital voltmeter for setting and monitoring the standard lamp voltage.

c) Spectral response measuring equipment with the following characteristics:

- constant-energy monochromatic light controlled at each wavelength with an automatic scanned monochromator,
- capable of both ac and dc measurements,
- white bias light which can be superimposed on mechanically chopped monochromatic light with a lock-in amplifier,
- temperature-control equipment for solar cell, and
- computer system for data processing.



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	AM0 white bias light source	6	Spectroradiometer
2	Monochromatic light source	7	Standard lamp
3	Pyroelectric radiometer	8	AM0 extraterrestrial reference
4	Solar cell		spectral irradiance
5	Solar simulator	9	Computer system

Figure 10 — Solar simulation calibration

8.5.3.4 Environmental conditions

The calibration shall be carried out in a laboratory whose temperature and humidity are maintained within the operational limits required by the test apparatus.

8.5.3.5 Test procedure

The solar simulator calibration method of an AM0 standard solar cell shall consist of measuring the short-circuit current of the cell under a solar simulator with an irradiance similar to the AM0 sunlight and correcting the measured short-circuit current against the AM0 sunlight using a spectroradiometer which had been previously calibrated by a standard lamp (traceable to national standard). The spectral irradiance accuracy calibrated by a standard lamp has been proved to be within ± 1 %. This calibration can be carried out at any time if a suitable measuring apparatus is prepared (Figure 11) and AM0 reference extraterrestrial sunlight irradiance is provided.

The calibration value of the short-circuit current under 1 367 $\mathrm{W \cdot m^{-2}}$ irradiance of the AM0 reference extraterrestrial sunlight is calculated by using:

$$Ic_{\text{sc cal}} = I_{\text{scm}} \frac{\int \Phi_{\text{s}\lambda} Q_{\lambda} \,\text{d}\lambda}{\int \Phi_{\text{m}\lambda} Q_{\lambda} \,\text{d}\lambda} \qquad (5)$$

The following is a summary of the calibration procedure:

a) The relative spectral response of the cell is measured at least three times with a white bias light of approximately 1 367 $\mathrm{W \cdot m^{-2}}$ (adjusted by a previously calibrated cell or a suitable detector) at a temperature of 25 °C ± 1 °C. Data without a white bias light may be used if the cell does not have the bias light effect. The data [Q_{λ}] is stored in a computer.

b) The irradiance in the test plane of the solar simulator is set at approximately 1 367 $\mathrm{W \cdot m^{-2}}$, by a previously calibrated cell or a suitable detector.

c) Keeping the same irradiance, the spectral irradiance in the test plane is measured by the spectroradiometer critically calibrated in a nonreflective place by a standard lamp (traceable to national standard). The data [$Q_{\text{m}\lambda}$] is stored in the computer.

d) The cell is positioned in the test plane of the solar simulator. While the cell temperature is maintained at 25 °C ± 1 °C, the short-circuit current of the cell is measured before and after a measurement of spectral irradiance described in procedure c). The averaged data [I_{scm}] is stored in the computer.

e) The calibrated I_{sc} for the solar cell is computed from the data by procedures a), c) and e).

f) Procedures b) to e) are repeated at least three times.

g) The mean value of $I_{\text{sc cal}}$ is fixed as the definitive calibration value.

8.5.4 Differential spectral response calibration method (PTB)

8.5.4.1 General

The calibration value is calculated from the measured absolute spectral response of the reference cell and the reference solar spectral irradiance distribution. The spectral response calibration is transferred from the standard detector irradiance level to the solar irradiance level over many orders of magnitude with no restrictions to the solar cell concerning linearity or spectral match.

8.5.4.2 Apparatus

The following apparatus is required (see Figures 11 and 12).

a) Intensity of monochromatic light of at least 1 mW·m^{-2} within the required wavelength range.

b) Lamp(s) with lens or mirror entrance optics (quartz-halogen lamp above 800 nm, Xenon arc source being better below 400 nm, and spectral lamp for wavelength recalibration).

c) Bias light source (an array or quartz halogen lamps with integrated parabolic dichroic mirrors recommended), where conformity to the spectral requirements of at most a Class C simulator (as defined in Annex G).

d) Chopped quasi-monochromatic beam for the absolute calibration at one or more discrete wavelength (with quartz-halogen lamp, chopper, 1 to 3 blocked narrow-band filters, having bandwidths of less than 20 nm centered at different wavelength between 500 nm and 900 nm, plane 45° mirror, i.e. without imaging optics).

e) Large-area monitor photodiode (or small-area photodiode with quartz lens; Si below 1 200 nm; InGaAs above 1 100 nm).

f) Radiation detector(s) with temperature control calibrated by an accredited calibration laboratory.

NOTE 1 Cryogenic radiometers are the recommended primary standards, which conform to the current World Radiometric Reference.

NOTE 2 These detectors should be high quality Si, or InGaAs above 1 100 nm, photodiodes with the best available linearity, uniformity and stability.

g) Two beam choppers with the same frequency.

h) Adjustable aperture (imaged onto the solar cell).

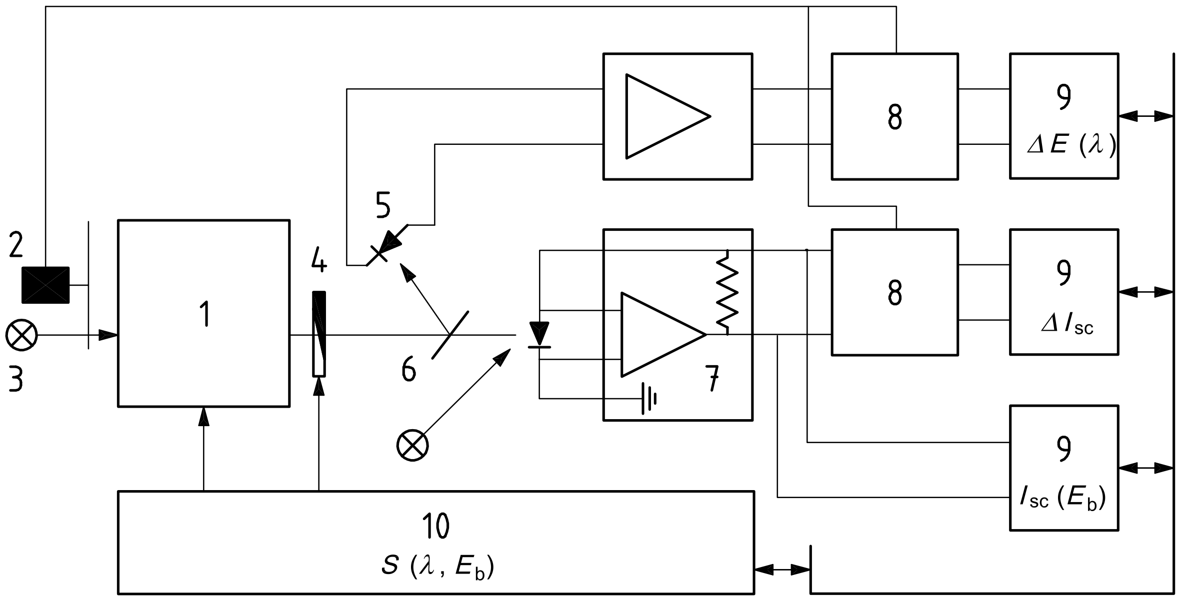
i) Means (temperature-controlled table) for maintaining the reference cell at 25 °C ± 1 °C.

j) Means for measuring the AC (including lock-in amplifiers) and DC short-circuit currents of the reference cell with a non-linearity of $< 0,1$ %; the same AC amplifiers are used for measuring the AC short-circuit current of the standard detector(s).

k) Computer system for control and data processing.

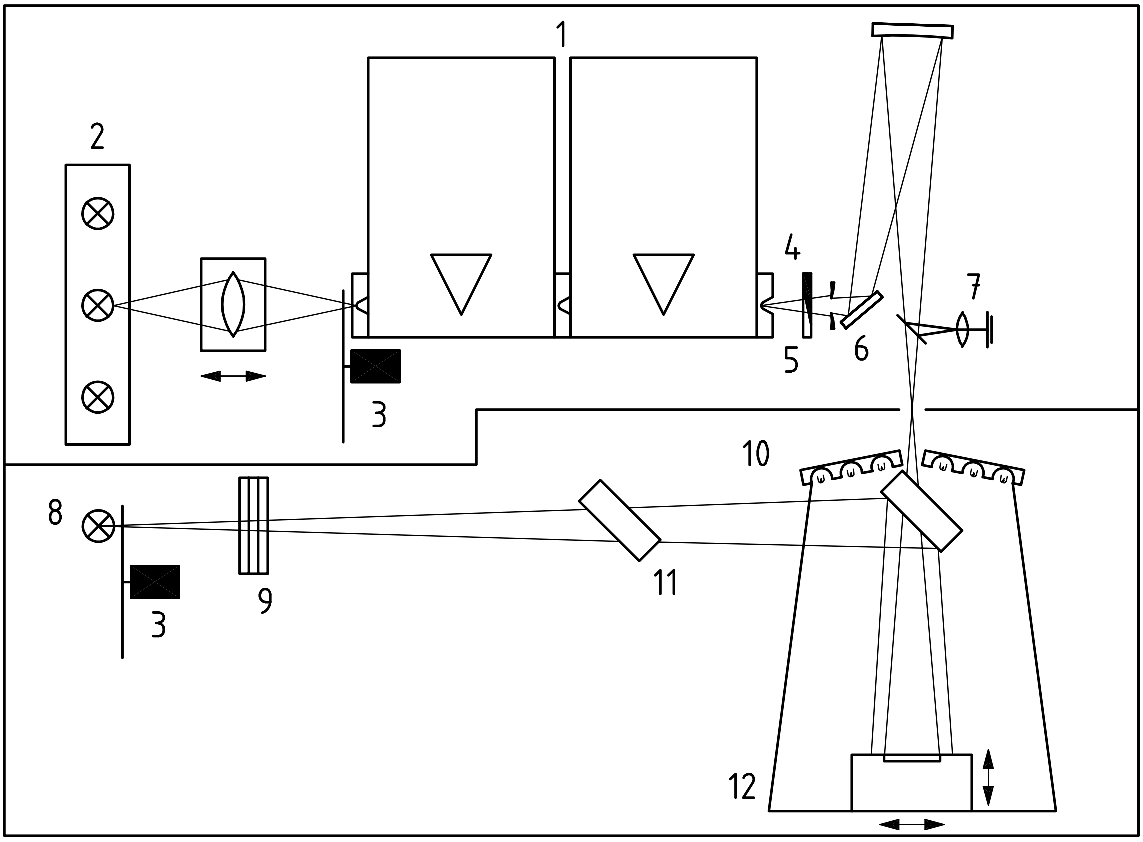
8.5.4.3 Environmental conditions

The calibration shall be carried out in a laboratory where the temperature and humidity are maintained within the operational limits required by the apparatus.



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	Digital Volt Multi Meter

Figure 11 — Block diagram of differential spectral response calibration



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Monochromator with triple grating turret	7	Narrowband Filter Set
2	Lamps	8	Lamp A
3	Chopper	9	Narrowband filter set
4	Aperture	10	Bias lamps with dichroic mirrors
5	Shutter	11	45° mirror
6	Beam splitter	12	Solar cell

Figure 12 — Optical arrangement of differential spectral response calibration

8.5.4.4 Test procedure

8.5.4.4.1 Set and maintain the temperature of the reference cell to 25 °C ± 1 °C.

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

8.5.4.4.3 Calibrate the spectroradiometer (without bias radiation) with respect to its relative spectral response by using its chopped monochromatic radiation and determining the ratio of the short-circuit currents of monitor photodiode ($\Delta I_{\mathrm{mon\ cal}}$) and standard detector (ΔI_{st}) measured simultaneously (using two lock-in amplifiers with identical time constants) at standard detectors is in a position close to the focus of the monochromatic beam collecting the whole radiation power.

8.5.4.4.4 Set the white bias irradiance E_b to the desired operational level, between 1 mW·m^{-2} and 2 000 W·m^{-2}, and measure the corresponding DC short circuit current $I_\mathrm{b} = I_\mathrm{sc}(E_\mathrm{b})$.

8.5.4.4.5 Measure the relative spectral response of the reference cell by using the chopped monochromatic radiation produced by the monochromator and determining the ratio of the short-circuit current of reference cell (ΔI_ref) and monitor photodiode (ΔI_mon) according to step (8.5.4.4.3) and calculate the relative differential spectral responsivity $s(\lambda, I_\mathrm{b})_\mathrm{rel}$ of the reference cell under bias irradiance E_b.

$$s(\lambda, I_\mathrm{b})_\mathrm{rel} = \frac{\Delta I_\mathrm{ref}}{\Delta I_\mathrm{mon}} \times \frac{\Delta I_\mathrm{mon\,cal}}{\Delta I_\mathrm{st}} S_\mathrm{st}(\lambda)$$

8.5.4.4.6 Repeat 8.5.4.4.4 and 8.5.4.4.5 at five or more different bias levels covering at least the range between 10 W·m^{-2} et 1 500 W·m^{-2}, thus including a linearity test.

8.5.4.4.7 With the white bias irradiance set as in 8.5.4.4.4 to one of the low levels $E_0 > 10$ W·m^{-2} avec $I_0 = I_\mathrm{sc}(E_0)$, measure the absolute spectral response of the reference cell at the three wavelengths represented by the narrowband filter set. This is done by using the chopped and filtered monochromatic radiation from the stabilized lamp A without imaging optics producing a uniform irradiance within the working plane of the reference cell. The absolute differential spectral response $s(\lambda, i, I_0)$ with $i = 1, 2, 3$ is determined by the ratio of short circuit current to irradiance, as measured by a standard detector in the working plane, with each filter in turn.

8.5.4.4.8 Take the mean value k_i of the ratio (relative spectral response/absolute spectral response) as determined in each of the three wavelengths under the E_0 irradiation.

8.5.4.4.9 Compute the absolute differential spectral responses:

$$s(\lambda, I_0) = (1/k) \times s(\lambda, I_\mathrm{b})_\mathrm{rel}$$

8.5.4.4.10 Compute the differential response $S_\mathrm{AM0}(I_\mathrm{b})$ under irradiation with AM0 reference solar spectral distribution at the five or more levels determined by I_b:

$$S_\mathrm{AM0}(I_\mathrm{b}) = \frac{\int s(\lambda, I_\mathrm{b}) E_{\mathrm{AM0}\,\lambda}(\lambda)\mathrm{d}\lambda}{E_\mathrm{STC}}$$

with

$$E_\mathrm{STC} = \int E_{AM0\,\lambda}(\lambda)\mathrm{d}\lambda = 1\,367 \text{ W} \cdot \text{m}^{-2}$$

where

I_b = $I_\mathrm{sc}(E_\mathrm{b})$

$E_{\mathrm{AMO}\,\lambda}(\lambda)$ is the air mass zero reference solar spectral irradiance distribution.

8.5.4.4.11 If the reference solar cell is linear, the variation of $S_\mathrm{AM0}(I_\mathrm{b})$ over 5 or more successive sets of measurements shall be less than ± 0,5 % (typical repeatability is better than ± 0,1 %). Take the mean of $S_\mathrm{AM0}(I_\mathrm{b})$ as the definitive spectral response under STC (Standard Test Conditions) $S_\mathrm{AM0} = I_\mathrm{STC}/E_\mathrm{STC}$.

NOTE If the reference cell is slightly nonlinear, the short-circuit current ISTC under STC is obtained by the following integration:

$$E_\mathrm{STC} = \int_0^{I_\mathrm{STC}} \Delta E / \Delta I_\mathrm{b} \cdot \mathrm{d}I_\mathrm{b} = \int_0^{I_\mathrm{STC}} 1/S_\mathrm{AM0} \cdot \mathrm{d}I_\mathrm{b}$$

where the upper integration limit I_STC is obtained by iterative approximation.

8.5.4.4.12 If it is desired to calibrate a nonlinear reference cell for more than one operational level of irradiance, repeat 8.5.4.4.3 and 8.5.4.4.9 for each of the desired levels.

9 Calibration of secondary AM0 standard solar cell

9.1 General

Secondary AM0 standard solar cells shall be calibrated in simulated sunlight against an AM0 standard (extraterrestrial AM0 standard and synthetic AM0 standard) solar cell.

The spectral response match between the AM0 standard solar cells and secondary AM0 standard solar cells shall be such that the spectral mismatch error under the illumination used for calibration is less than ± 1 % as determined by the procedure given in Annex B.

9.2 Solar simulator

If simulated sunlight is used, the solar simulator shall be of Class A in accordance with Annex G.

9.3 Ground level sunlight (if needed)

Calibration in ground level sunlight shall be carried out under the following conditions:

a) Clear weather, sunny weather, with the diffuse irradiance not greater than 25 % of the global irradiance;

b) No observable cloud formations within a 30° half-angle cone surrounding the sun;

c) Total irradiance (sun + sky + ground reflection) not less than 800 $\mathrm{W \cdot m^{-2}}$, as measured by the AM0 standard solar cell;

d) Air mass between AM1 and AM2; and

e) Radiation sufficiently stable so that the variation in AM0 standard solar cell short-circuit current is less than ± 0,5 % over the time taken for a measurement.

9.4 Calibration procedure

a) Before the calibration, measure the relative spectral response and temperature coefficient of short-circuit current of the secondary AM0 standard solar cell, using the procedures specified in Annexes C and D.

b) Mount the AM0 standard and the secondary AM0 standard solar cells coplanar and in close proximity on the same mount. Connect to the current and temperature measuring instruments. If possible, control the cell temperature at 25 °C ± 1 °C. If it is not practicable to control the temperature of the cells, shade them from the light except when current measurements are taken. (Shading is not necessary with pulse simulators.)

c) Adjust the mount so that the solar beam or centerline of the simulator beam is normal to the cell surfaces within ± 5°.

d) Record simultaneous readings of the short-circuit currents and temperature of both standard solar cells.

e) Repeat step d) 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 ± 1 %.

f) When calibrating in natural sunlight, repeat the steps b) through e); a minimum of five times on at least three separate days.

g) From the acceptable data, calculate the mean ratio:

$$\frac{\text{Short-circuit current of secondary reference cell at 25 °C}}{\text{Short-circuit current of primary reference cell at 25 °C}}$$

h) Multiply the calibration value of the AM0 standard solar cell by the calculated mean ratio to obtain the calibration value of the secondary AM0 standard solar cell.

Annex A
(normative)

Measurement of current-voltage characteristics

A.1 General

This International Standard describes measurement procedures for current-voltage characteristics of crystalline silicon solar cells in natural or simulated sunlight. These procedures are applicable to a single junction solar cell.

NOTE These procedures are limited to linear solar cells.

A.2 General measurement requirements

a) The irradiance measurements shall be made with a calibrated reference solar cell as specified in Clause 8.

b) The reference solar cell shall have essentially < 0,5 % spectral response variation over the spectral range of the test cell specimen and shall be selected and calibrated in accordance with Clause 8.

c) The temperature of the reference solar cell and specimen shall be measured to an accuracy of ± 1 °C. If the temperature of the reference solar cell differs by more than 2 °C from the temperature at which it was calibrated, the calibration value shall be adjusted to the measured temperature.

d) The active surface of the specimen shall be coplanar within ± 1° for cells and within ± 5° for arrays by module with the active surface of the reference solar cell. No collimators shall be used on the test specimen.

e) Test connections are shown in Figure A.1.

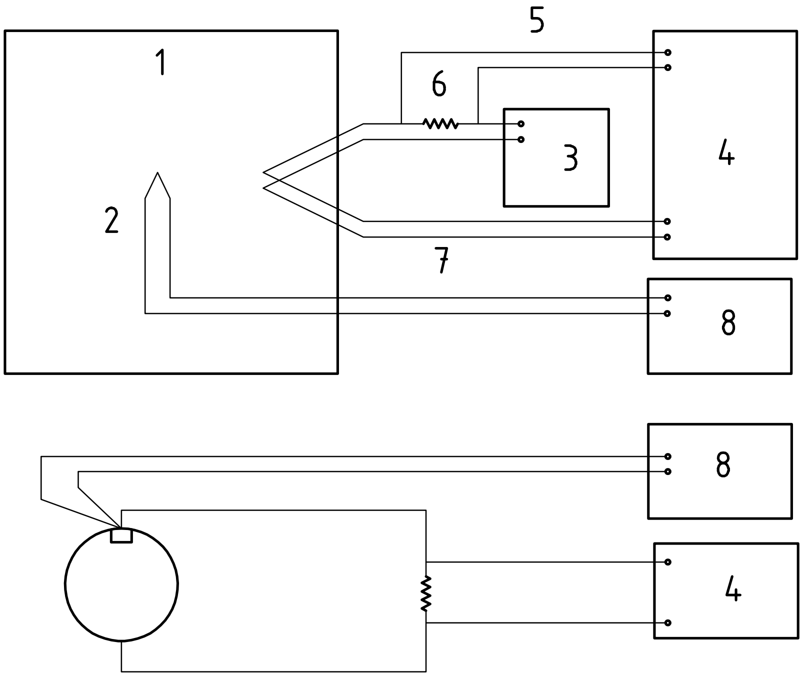
f) Voltages and currents shall be measured to an accuracy of ± 0,5 % by using independent leads from the terminals of the specimen.

g) Short-circuit currents shall be measured at zero voltage, using a variable bias (preferably electronic) to offset the voltage drop across the external series resistance. Alternatively, they may be determined by measuring the voltage drop across a precision four-terminal fixed resistor (precision resistor of known value within ± 0,1 % and $\sim 10^{-5}$/°C drift) provided that a measurement is made at a voltage not higher than 3 % of the cell opencircuit voltage, within the range where there is a linear relationship between current and voltage, and the curve is extrapolated to zero voltage.

h) Voltmeters shall have an internal resistance of at least $1\ \mathrm{M\Omega \cdot V^{-1}}$.

i) The calibration of all instruments shall be certified to be within the required accuracy at the time of measurement as specified by manufacturer.

j) The accuracy of the correction procedures for irradiance and temperature shall be verified periodically by measuring the performance of a specimen at selected levels and comparing the results with corresponding extrapolated data.



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Specimen	5	Current
2	Temperature sensor	6	Precision resistor
3	Variable load	7	Voltage
4	Electronic measurement equipment	8	Temperature monitor

Figure A.1 — Test connections

A.3 Measurements in natural sunlight

Measurements in natural sunlight shall be made only when the total irradiance (sun+sky) is not fluctuating by more than ± 1 % during a measurement. When the measurements are intended for reference to standard test conditions the irradiance shall be at least 800 $W \cdot m^{-2}$.The test procedure is as follows.

a) Mount the reference solar cell as near as possible to, and coplanar with, the specimen. Both shall be normal to the direct solar beam within ± 10°.

b) Record the current-voltage characteristic and temperature of the specimen concurrently with recording the short-circuit current and temperature of the reference solar cell. If it is not practical to control the temperature, shade the specimen and/or solar cell from the sun and wind until its temperature is uniform with the ambient air temperature. Make the measurements immediately after removing the shade.

NOTE In most cases, the thermal inertia of the specimen or solar cell will limit the temperature rise during the first few seconds to less than 2 °C and its temperature will remain reasonably uniform.

c) Correct the measured current-voltage characteristic to the desired irradiance and temperature conditions in accordance with 5.1.

A.4 Measurement in steady-state simulated sunlight

Steady-state sunlight simulation for solar cell performance measurements shall meet the requirements of Annex F. The test procedure is as follows:

a) Mount the reference solar cell with its active surface in the test plane so that the normal of the solar cell is parallel within ± 5 % to the center line of the beam.

b) Set the irradiance at the test plane so that the reference solar cell produces its calibrated short-circuit current at the desired level.

c) Remove the reference solar cell and mount the specimen as desired in a).

NOTE If the beam is sufficiently wide and uniform the specimen can be mounted beside the reference solar cell.

d) Without changing the simulator setting, record the current-voltage characteristic and temperature of the specimen. Where it is not practical to control the temperature, shade the specimen and/or the solar cell from the simulator beam until the solar cell temperature is uniform within ± 2 °C at ambient air temperature. Make the measurement immediately after removing the shade [see applicable note in A.3 b)].

e) If the temperature of the specimen is not the desired temperature, correct the measured current-voltage characteristic to this desired temperature using the procedure in accordance with Annex D.

A.5 Measurement in pulsed simulated sunlight

Pulsed sunlight simulation for solar cell performance measurements shall meet the requirements of Annex F. The test procedure is as follows:

a) Mount the specimen as near as possible to the reference solar cell with the active surfaces in the test plane. The normal of the specimen and the reference solar cell shall be parallel within ± 5° to the center at the desired level.

b) Set the irradiance at the test plane so that the reference solar cell produces its calibrated short-circuit current at the desired level.

NOTE In some pulse simulators, the pulse is triggered by a separate solar cell when the irradiance reaches a level which has been previously set with a reference solar cell.

c) Record the current-voltage characteristic and temperature of the specimen (or ambient temperature, if it is the same). The time interval between the data points shall be sufficiently long to ensure that the response time of the test specimen and the rate of data collection will not introduce errors.

d) Correct the measured current-voltage characteristic to both the desired temperature and irradiance in accordance with Annex D.

A.6 Test report

When a test report is required, it shall contain the following data:

- A description and identification of the specimen (solar cell, subassembly of solar cells or module),
- Test environment (natural or simulated sunlight and, in the latter case, brief description and class of simulator),
- Irradiance level,

- Temperature of the specimen and reference solar cell,
- Description and identification of primary and/or secondary reference solar cell (cell or module),
- Calibration data (where and when calibrated, calibration value),
- Deviations from standard test procedures, and
- Test results.

Annex B
(normative)

Computation of spectral mismatch error

B.1 General

This annex describes the procedure for determining the error introduced in the testing of a solar cell caused by the interaction of the mismatch between the spectral responses of the test specimen and the reference solar cell, and the mismatch between the test spectrum and the reference spectrum. The procedure applies only to linear solar cells.

Cell mismatch error should be kept to a minimum, linear implies that the cell I_{sc} varies directly (linearly) with varying intensity (fixed spectral illumination). That is X suns × I_{sc} (1 sun).

B.2 Description of method

The error is computed from the integrated products of the relative spectral responses of the reference solar cell and the test specimen and the relative spectral irradiance of the simulator and the reference solar spectral irradiance distribution as defined in Clause 5.

Thus if

J_1	is the short-circuit current density of the reference cell in solar radiation having an irradiance of 1 367 $\mathrm{W{\cdot}m^{-2}}$ and the reference spectral irradiance ($\mathrm{A{\cdot}m^{-2}}$)
J_2	is the short-circuit current density of the reference cell, as measured in extraterrestrial or simulated sunlight ($\mathrm{A{\cdot}m^{-2}}$)
$S_{1\lambda}$	is the absolute spectral response of the reference cell, at wavelength λ ($\mathrm{A{\cdot}W^{-1}}$)
$K_1\ S_{1\lambda}$	is the relative spectral response of the reference cell at wavelength λ
J_3	is the short-circuit current density of the test specimen in solar radiation having an irradiance of 1 367 $\mathrm{W{\cdot}m^{-2}}$ and the reference spectral irradiance ($\mathrm{A{\cdot}m^{-2}}$)
J_4	is the short-circuit current density of the test specimen, as measured in the extraterrestrial, natural sunlight or simulated solar radiation ($\mathrm{A{\cdot}m^{-2}}$)
$S_{2\lambda}$	is the absolute spectral response of the test specimen at wavelength λ ($\mathrm{A{\cdot}W^{-1}}$)
$K_2\ S_{2\lambda}$	is the relative spectral response of the test specimen at wavelength λ
$G_{\mathrm{s}\lambda}$	is the absolute spectral irradiance at wavelength λ of the reference spectral irradiance ($\mathrm{W{\cdot}m^{-2}}$ $\mathrm{\mu m^{-1}}$)
$K_3\ G_{\mathrm{s}\lambda}$	is the relative spectral irradiance at wavelength λ of the reference spectral irradiance
$G_{\mathrm{t}\lambda}$	is the absolute spectral irradiance at wavelength λ of the extraterrestrial, natural or simulated solar radiation ($\mathrm{W{\cdot}m^{-2}{\cdot}\mu m^{-1}}$)
$K_{4\lambda}G_{\mathrm{t}\lambda}$	is the relative spectral irradiance at wavelength λ of the extraterrestrial, natural or simulated solar radiation

Then

$$J_1 = \int S_{1\lambda}\ G_{s\lambda}\ d\lambda$$

$$J_2 = \int S_{1\lambda}\ G_{t\lambda}\ d\lambda$$

$$J_3 = \int S_{2\lambda}\ G_{s\lambda}\ d\lambda$$

$$J_4 = \int S_{2\lambda}\ G_{t\lambda}\ d\lambda$$

Integration of the products of the measured relative spectral responses and the relative spectral irradiance yields the following parameters:

$$A_1 = \int K_1\ S_{1\lambda}\ K_3\ G_{s\lambda}\ d\lambda = K_1\ K_3\ J_1$$

$$A_2 = \int K_1\ S_{1\lambda}\ K_4\ G_{t\lambda}\ d\lambda = K_1\ K_4\ J_2$$

$$A_3 = \int K_2\ S_{2\lambda}\ K_3\ G_{s\lambda}\ d\lambda = K_2\ K_3\ J_3$$

$$A_4 = \int K_2\ S_{2\lambda}\ K_4\ G_{t\lambda}\ d\lambda = K_2\ K_4\ J_4$$

$$I_{\text{sc corr}} = I_{\text{sc meas}} \times (A_3 \times A_2)/(A_1 \times A_4)$$

$I_{\text{sc corr}}$ is the corrected short-circuit current of the test specimen for the reference spectrum. $I_{\text{sc meas}}$ is the measured short-circuit current of the test specimen under the extraterrestrial, natural or simulated spectrum.

Annex C
(normative)

Measurement methods of the spectral response

C.1 General

This annex gives guidance for the measurement of the relative spectral response of both linear and nonlinear solar cells.

NOTE In this International Standard the word monochromatic is used to mean narrow bandwidth.

C.2 Relative spectral response measurement

The relative spectral response of a solar cell is measured by irradiating it by means of a narrow-bandwidth light source at a series of different wavelengths covering its response range, and measuring the short-circuit current density and irradiance at each of these wavelengths.

NOTE In this International Standard, the words sunlight and light are used in their broader sense to include the ultraviolet and the infrared as well as the visible spectrum.

The light source should irradiate the cell uniformly and the temperature of the cell should be controlled. The current densities are then divided by the irradiances or a proportional parameter and plotted as a function of wavelength. Alternatively, the irradiance may be kept constant (for instance, by varying the width of a monochromator exit slit), in which case the relative spectral response is obtained directly from the current density readings. Spectral irradiance shall be measured according to Annex H.

The irradiance monitor may be a vacuum thermocouple, a pyroelectric radiometer or other suitable detector. Another alternative is a previously calibrated reference solar cell whose relative spectral response covers the required range. In this case, $k_2 S_{2\lambda}$, the relative spectral response of the test specimen at wavelenght λ is completed as follows:

$$k_2 S_{2\lambda} = k_1 S_{1\lambda} \frac{J_{\mathrm{mt}\lambda}}{J_{\mathrm{mr}\lambda}}$$

where

$k_1 S_{1\lambda}$ is the relative spectral response of the solar cell at wavelength λ;

$J_{\mathrm{mt}\lambda}$ is the measured short-circuit current density of the test specimen at the same wavelength λ;

$J_{\mathrm{mr}\lambda}$ is the measured short-circuit current density of the reference solar cell at the same wavelength λ.

In assembling the test setup and performing the measurements, special attention should be given to the following:

- uniformity of irradiance at the test plane;

NOTE Uniform irradiance is very important when test specimen and reference solar cells are of different dimensions.

- filter transmission curves

NOTE The curves should be checked periodically to detect any sideband transmission.

- load resistor value, calibration and contact resistance

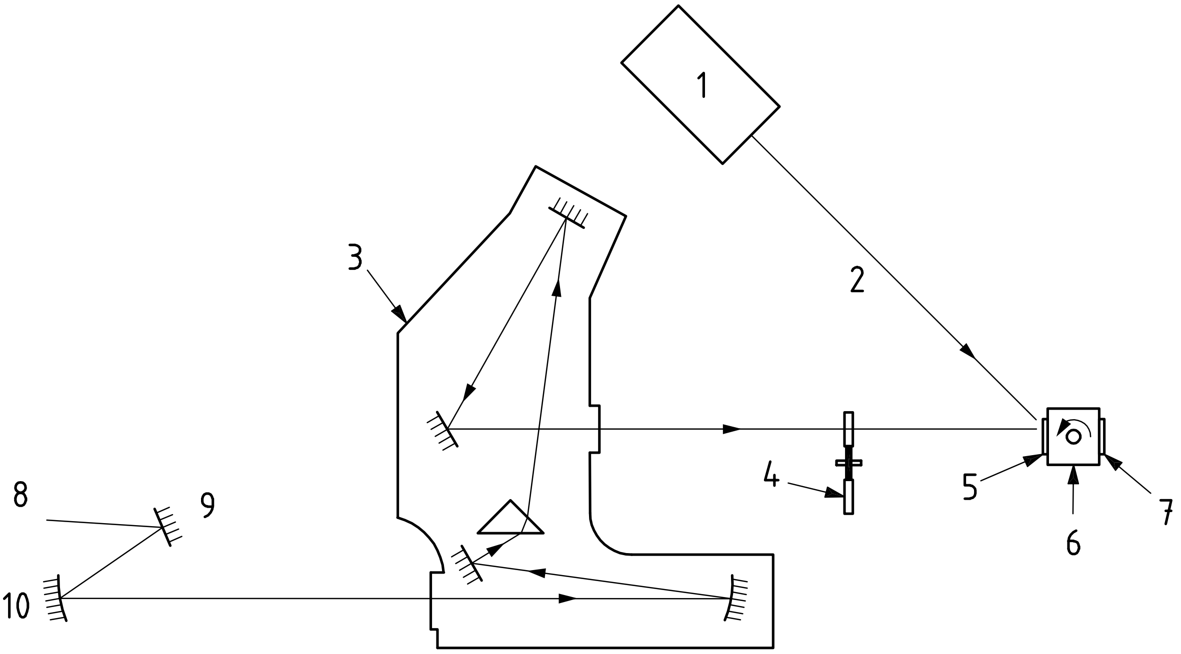
NOTE The load resistor should be kept to a minimum practical value in order to remain as close as possible to true short-circuit conditions.

- linearity of response of the short-circuit current of the solar cell versus the light intensity at all illumination levels and all wavelengths.

Annex I provides requirements for measurement of linearity.

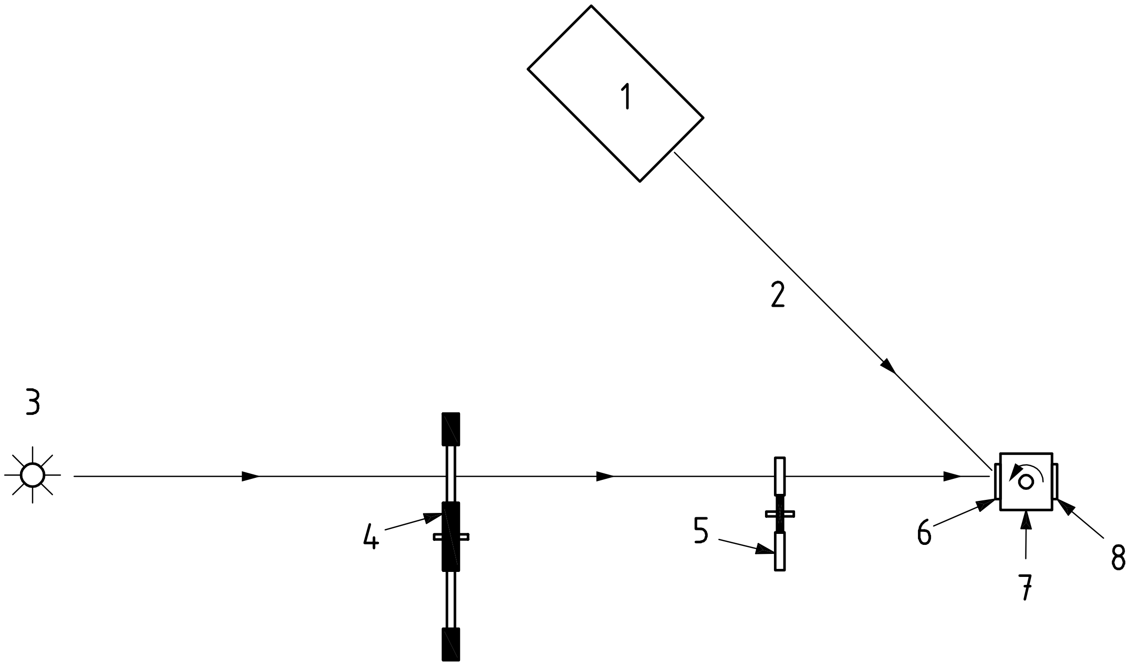
Figures C.1 and C.2 show two examples of test arrangements, the first embodying a quartz prism monochromator and the second a filter wheel as the monochromatic source.

In both cases, the light source is a 1 000-W tungsten halogen lamp operated from a stable supply at a colour temperature of 3 200 K. The test cell and the irradiance monitor are mounted on opposite sides of a rotatable temperature-controlled block, so that either may be presented to the monochromatic beam in precisely the same place. Alternatively, they may be mounted on a slide with suitable positioning stops or illuminated simultaneously by means of a beam splitter.



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Solar simulator	6	Rotatable temperature-controlled mount
2	Bias light	7	Radiometer or reference cell
3	Monochromator	8	Light source
4	Chopper	9	Plane mirror
5	Test specimen	10	Concave mirror

Figure C.1 — Spectral response measurement using a monochromator



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Solar simulator	5	Chopper
2	Bias light	6	Test specimen
3	Light source	7	Rotatable temperature- controlled mount
4	Filter wheel	8	Radiometer or reference cell

Figure C.2 — Spectral response measurement using a filter wheel

The filter wheel should contain a sufficient number of narrow-band filters to cover the response range of the cell in wavelength steps not exceeding 50 nm. The filters are arranged so that each can be indexed in turn between the light source and the test cell or irradiance monitor. It is important that the filters have negligible (< 2 %) sidebands. The monochromator is normally used with fixed slits and manually set to the same wavelength steps.

With crystalline silicon and other cells where the response has been shown to change linearly with irradiance, the short-circuit current of the cells (voltage drop across a standard four-terminal fixed resistor) and the open-circuit voltage of the vacuum thermocouple or radiometer may be measured directly with a DC digital voltmeter or potentiometer. The requirements for instrumentation accuracy and the measurement of short-circuit currents are given in Annex A. If the DC method is used, the exit beam, test specimen and irradiance monitor should be completely enclosed in an antireflective light-tight box and meticulous precautions should be taken to avoid thermal and other random electromagnetic fields which would cause errors. Alternatively, the exit beam may be chopped at a low frequency and the output voltage amplified and rectified. In this case, it is important to ensure that the amplifiers are linear and drift free.

With nonlinear solar cells it is necessary to use a chopped monochromatic beam and to increase the irradiance to the desired operational level (e.g. 1 367 $W \cdot m^{-2}$) by using unmodulated bias light from a suitable steady-state simulator as shown in Figures C.1 and C.2. For linear solar cells the bias light is also necessary unless there is proof that the obtained spectral response will not change significantly when the bias light is not used.

Another way to obtain illumination intensity sufficiently high to operate the solar cell in the linear response domain after the light beam has gone through the monochromatic filters is to use a flash as a light source. The energy pulse being short does not heat up the filters. This method is illustrated by Figure C.3. In addition to the customary filter wheel, light-tight box, sample holder and reference solar cells as previously described, the test setup comprises:

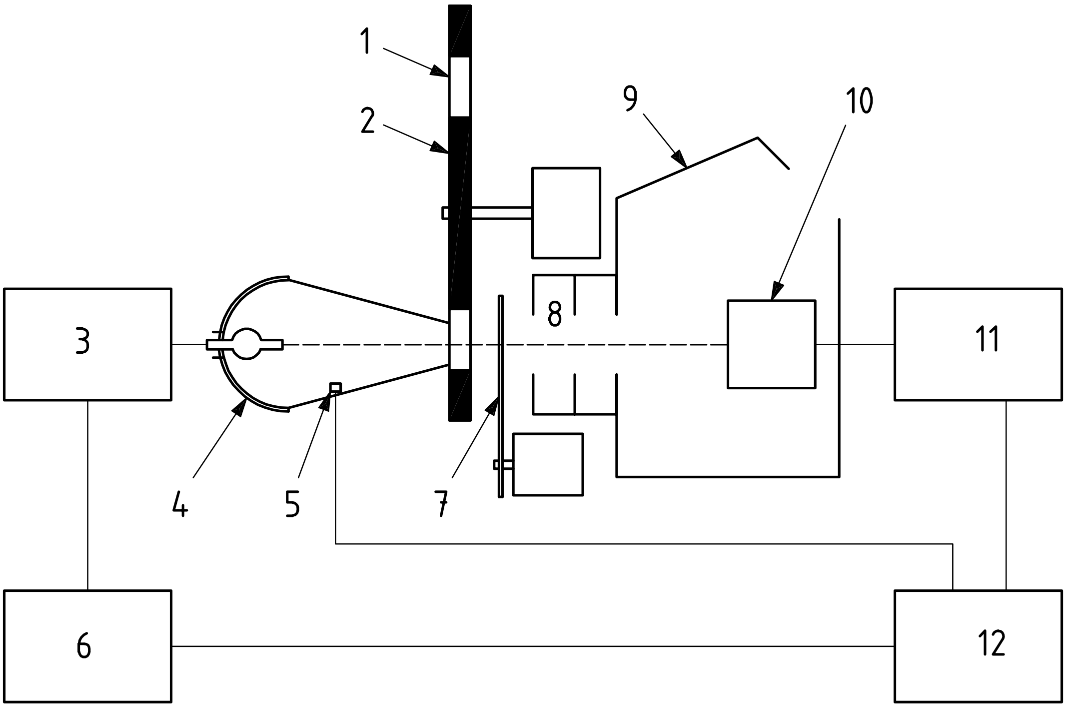
- a photoflash lamp that provides high intensity light pulses,
- a light pulse intensity monitor, and
- an electronic peak detector.

Therefore, apart from the change of light source, the measurement method remains the same, based on the comparison of the short-circuit currents generated respectively by the cell to be measured and by the spectrally calibrated cell. This comparison and the correction for the pulse-to-pulse slight variations of light intensity are done by the computer.

The pulsed spectral response method requires the same precautions as the continuous or chopped illumination ones; namely

- uniformity of irradiance at the test plane,
- periodic checking of filter transmission curves, contact resistance and load calibration,
- operation of cells near short-circuit and
- linearity of short-circuit current versus light intensity at all wavelengths. Concerning this last item, combination with bias-light illumination is also possible.

NOTE The critical cell characteristic for this method is response time. Although most crystalline Si and GaAs solar cells have a response fast enough in short-circuit mode, this has to be verified before the measurement on both test and AM0 standard solar cells by using a memory oscilloscope, for example.



Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Interference filter	7	Shutter
2	Filter wheel	8	Light box
3	Power supply	9	Lid
4	Flash lamp	10	Rotating sample holder
5	Light pulse intensity monitor	11	Electronic load
6	Computer	12	Peak detector

Figure C.3 — Experimental test setup for pulsed spectral response measurement

Annex D
(normative)

Procedures for temperature and irradiance corrections

D.1 General

This annex describes the procedures for temperature and irradiance corrections to the measured current-voltage characteristics of crystalline silicon solar cells. It includes procedures for the determination of temperature coefficients, internal series resistance and curve correction factor. These procedures are applicable over an irradiance range of ± 30 % of the level at which the measurements were made.

NOTE 1 These procedures are limited to linear solar cells.

NOTE 2 The solar cells include a single solar cell, a sub-assembly of solar cells, or an array. A different set of values applies for each type of solar cell. Although the determination of temperature coefficients for a module (or sub-assembly of cells) may be calculated from single cell measurements, it should be noted that the internal series resistance and curve correction factor should be separately measured for a module or sub-assembly of cells.

NOTE 3 The term “test specimens” is used to denote any of these cells.

D.2 Correction procedures

The measured current-voltage characteristic shall be corrected to standard test conditions or other selected temperature and irradiance value by applying the following equations:

$$I_2 = I_1 + I_{\mathrm{sc}} \left(\frac{I_{\mathrm{sr}}}{I_{\mathrm{mr}}} - 1 \right) + \alpha (T_2 - T_1)$$

$$V_2 = V_1 + R_{\mathrm{s}} (I_2 - I_1) - K \cdot I_2 (T_2 - T_1) + \beta (T_2 - T_1)$$

where

I_1, V_1 are the coordinates of points on the measured characteristics;

I_2, V_2 are the coordinates of the corresponding points on the corrected characteristic;

I_{sc} is the measured short-circuit current of the test specimen;

I_{mr} is the measured short-circuit current of the reference solar cell corrected, as necessary, to the temperature of the reference solar cell during the measurement of I_{MR};

I_{sr} is the measured short-circuit current of the reference solar cell at the standard or other desired irradiance;

T_1 is the standard or other desired temperature;

T_2 is the measured temperature of the test specimen;

α, β are the current and voltage temperature coefficients of the test specimen in the standard or other desired irradiance and within the temperature range of interest (β is negative);

R_{s} is the internal series resistance of the test specimen;

K is the curve correction factor.

D.3 Determination of temperature coefficients

The temperature coefficients of current (α) and voltage (β) vary with irradiance and to a lesser extent, with temperature. The procedure is as follows:

a) Attach a temperature sensor to the test cell so that the temperature can be measured to an accuracy of ± 0,5 °C.

b) Mount the test cell with good thermal contact to a temperature-controlled block, and use the attached sensor to provide the control signal.

c) Mount the test cell as near as possible to a suitable reference solar cell with the active surfaces in the test plane. The normal of the test cell and the reference solar cell shall be parallel within ± 5° to the centerline of the beam.

d) Set the irradiance at the test plane so that the reference solar cell (at 25 °C ± 5 °C) procedure is calibrated short-circuit current at the desired level.

e) With the test cell stabilized at or near the minimum temperature of interest, measure its short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}).

NOTE At subambient temperature, precautions may be necessary to prevent condensation on the active surfaces of the test cell and reference solar cell. This precaution could be accomplished by passing dry nitrogen gas over the active surfaces or by enclosing the cells in a vacuum chamber.

f) Stabilize the test cell at a temperature approximately 10 °C above the previous level and repeat I_{sc} and V_{oc} measurements. Repeat this procedure at approximately 10 °C increments up to the maximum temperature of interest.

g) Repeat the steps a) to f) on each of the other test cells.

h) Plot the values of I_{sc} and V_{oc} as a function of temperature and construct a least-squares fit curve through each set of data.

i) From the slopes of the current and the voltage curves and at a point midway between the minimum and maximum temperature of interest, calculate α_{c} and β_{c}, the temperature coefficients for single cells.

j) For a module or other subassembly of cells, calculate the temperature coefficients as follows:

$$\alpha = n_{\mathrm{p}} \alpha_{\mathrm{c}}$$

$$\beta = n_{\mathrm{s}} \beta_{\mathrm{c}}$$

where n_{p} is the number of cells in parallel and n_{s} is the number of series.

D.4 Determination of internal series resistance

R_{s} may be determined in simulated sunlight by the following procedure (see Figure D.1) where series resistance is dependent on intensity and should be noted as such:

a) Trace the current-voltage characteristic of the test specimen at room temperature and at two different irradiances (magnitudes need not be known). During the two measurements the cell temperature shall not differ by more than 2 °C.

b) Choose a point P on the higher characteristic, at a voltage slightly higher than $V_{\mathrm{P\,max}}$. Measure ΔI, the difference between the current at this point and I_{sc1}.

c) Determine the point Q on the lower curve at which the current is equal to $I_{sc2} - \Delta I$.

d) Measure the voltage displacement ΔV between points P and Q.

e) Calculate R_{s1} from

$$R_{s1} = \frac{\Delta V}{I_{sc1} - I_{sc2}}$$

where I_{sc1} et I_{sc2} are the two short-circuit currents.

f) Repeat c) to e), using a characteristic taken at a third irradiance level and the same cell temperature, in combination with each of the first two curves to determine value of the R_{s2} and R_{s3}.

g) R_s is the mean of the three calculated values: R_{s1}, R_{s2} et R_{s3}.

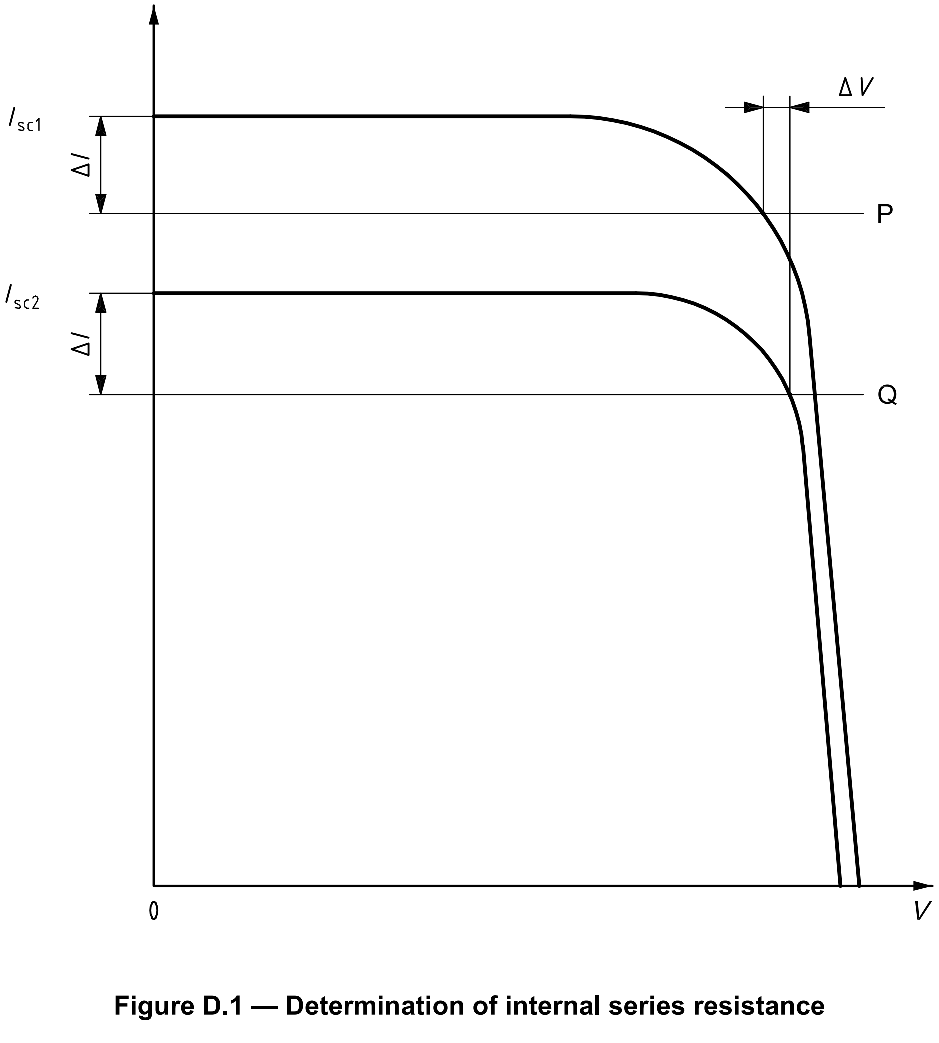


Figure D.1 — Determination of internal series resistance

D.5 Determination of curve correction factor

K may be determined in simulated sunlight by the following procedure:

a) Trace the current-voltage characteristic of the test specimen irradiance within ± 30 % of the selected level and at three different temperatures (T_3, T_4 and T_5) over an interest range of at least 30 °C.

NOTE When measuring the characteristics of a module, precautions should be taken (for instance by enclosing the module in a temperature controlled chamber with a transparent window) to ensure uniformity of the cell temperature within ± 2 °C of the intended level.

b) Using an assumed value of K (say $1{,}25 \times 10^{-3}\ \Omega\cdot{}^\circ\mathrm{C}^{-1}$ which is typical for a crystalline silicon cell) transpose the characteristic measured at temperature T_3 to temperature T_4 by applying the following equations:

$$I_4 = I_3 + \alpha\,(T_4 - T_3)$$

$$V_4 = V_3 - KI_4\,(T_4 - T_3) + \beta\,(T_4 - T_3)$$

where

I_3, V_3 are coordinates of points on the T_3 temperature characteristic;

I_4, V_4 are coordinates of the corresponding points on the T_4 temperature characteristic.

c) If the transposed T_4 temperature characteristic does not coincide with the desired accuracy to that obtained by measurement, repeat step in b) by inserting different values for K until the transposed T_4 temperature characteristic and the measured characteristic coincide.

d) When the proper value of K has been determined, transpose the T_3 and T_4 characteristics sequentially to match the characteristic at temperature T_3. If the transposed and corresponding measured characteristic do not coincide, repeat the transposition with a slightly different value of K until the value for a correct fit is determined in each case.

e) Use the mean of the three values of K thus determined.

Annex E
(normative)

Uncertainty analysis of AM0 standard solar cell calibration

E.1 Typical error sources

The typical error sources relevant for AM0 standard solar cell calibration are as follows.

a)	Electrical	Voltmeter(s)
		Instrumentation shunt resistor
		Thermovoltages
		Temperature of all instruments
		Temperature fluctuations of shunt
		Internal heating of shunt by load
		Linearity of current converter
		Noise of equipment in case of outdoor mV measurement
		Temperature measurement
b)	Optical set-up	Beam divergence
		Non-normal incidence
		Multiple reflections
		Stray light
		Shadowing by probes
		Non-uniformity of light
		Pointing error towards sun
		Light fluctuations
		Temporal stability
c)	Spectral response of	Linearity of lock-in amplifier (LIA)
		Test cell
		Linearity of current converters
		Temperature coefficient of shunt, LIA and LIA output
		Calibration error of reference
		Wavelength error
		Change of band edge of cell by temperature error
		Suppression of higher orders
		Linearity of test cell
d)	Spectrum	Calibration error of spectroradiometer measurement
		Field of view in comparison to reference and test cell
		Temperature of spectroradiometer

		Wavelength error
		Light fluctuations during scan time
e)	Test cell	Intrinsic non-uniformity of cell
		Non-ideal cosine response
		Linearity
		Difference in time constant between reference and test cell
		Field of view
		Temporal stability
f)	Reference element	Uncertainty of pyranometer
		Absolute cavity radiometer
		Degradation of calibration
		Variation of spectral properties (degradation of black paints)
		Non-ideal cosine response
		Time constant
		Field of view
		Cosine response

E.2 Uncertainty analysis

The typical uncertainty analysis for the each AM0 standard solar cell calibration method is as follows.

NOTE The proposed uncertainty analysis data for each of the seven calibration methods are shown below.

Table E.1 — Uncertainty summary of balloon flight calibration method (JPL)

Error source		**Error contribution**	
		mV	%
V_{cell}	Amplifier calibration	0,015 3	0,022 6
$V_{\text{A/D}}$	A/D dither	0,025 1	0,037 0
R	Earth-sun angle	0,002 7	0,040
—	Off-normal angle	0,023 6	0,034 8
T_{co}	Temperature coefficient	0,132	0,0195 2
T	Cell temperature	0,104 6	0,010 46

NOTE 1 See 8.4.1.

NOTE 2 The square root of the sums of the error contributions squared gives an overall standard deviation of 0,25 %.

Table E.2 — Uncertainty summary of balloon flight calibration method (CNES)

Source of error	Typical value
Errors caused by pointing imprecision	± 0,3°
Errors linked to correction factors	
1. Residual absorption[a]	2 %
2. Variation of sun-earth distance[b]	3,5 %
Errors linked to numeric analogic conversion	
The digital to analogic converter is given with an accuracy of	$\pm 2,5 \times 10^{-4}$
Errors linked to the measurement system:	
1. Resistor (I_{sc})	1×10^{-5}
2. On the temperature	< 1 %
3. On the amplifier gain $\Delta G/G$	$> 10^{-3}$

NOTE 1 See 8.4.2.

NOTE 2 The arithmetical sum of these errors leads to a calibration error of 0,5 % to 0,7 %.

[a] This overestimation coefficient is calculated from the values of the spectral response of each solar cell. However, its very weak value caused an error on current measurement less than 5×10^{-4}.

[b] This coefficient is estimated within 1% and induces a calibration error less than 5×10^{-4}.

Table E.3 — 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)	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

NOTE See 8.4.3.

Table E.4 — Uncertainty summary of global sunlight calibration method (INTA-Spasolab)

Source of error	Typical value %
Short-circuit current	± 0,05
Global irradiance	± 1,30
Spectral global sunlight irradiance measurement	± 0,09
Spectral response system and AM0 values	± 0,08
Spectral response system and spectral global sunlight irradiance	± 0,50
Calibration short-circuit current	± 0,40
NOTE See 8.5.1.	

Table E.5 — Uncertainty summary of direct normal sunlight calibration method (CAST)

Source of error	Bias error %	Random error %
I_{sc} measurement	0,02	0,02
I_{sc} time constants	0,00	0,20
Absolute cavity radiometer	0,37	0,13
Spectral correction factor	0,00	0,20
Temperature correction factor	0,00	0,05
Thermal offset voltages	0,05	0,05
Total	0,37	0,32
NOTE See 8.5.2.		

Table E.6 — Uncertainty summary of solar simulator calibration method (NASDA)

Source of error	Typical value (%)
Uncertainty of the standard lamp	< 3,5
Uncertainty due to spectroradiometer	< 0,02
Uncertainty due to measurement repeatability.	< 0,94
Combined expand uncertainty (U_{95})	< 3,63
NOTE See 8.5.3.	

Table E.7 — Uncertainty summary of differential spectral response calibration method (PTB)

Source of error	**Typical value** (k = 2) %
Uncertainty of the standard detector(s)	< 0,5
Uncertainty due to nonlinear or narrow-band cells	< 0,1
Uncertainty due to unstable cell temperature (± 1K)	< 0,1
Transfer uncertainties due to	—
relative spectral response	0,1
absolute spectral response at discrete wavelength(s)	0,1
spectral mismatch between bias radiation and reference solar	0,5
Combined expanded uncertainty:	< 1
spectrum; non-uniformity of bias radiation	—
non-uniformity of monochromatic radiation	—
mismatch of cell area and irradiated area (image of the diaphragm)	—
spectral bandwidth (< 20 nm) of the monochromatic radiation	—
non-linearity of the amplifiers	—

NOTE 1 See 8.5.4.

NOTE 2 In this table, typical values on the uncertainty components resulting in a combined expanded uncertainty of $U_{95} < 1$ %, with coverage factor k = 2, are summarized. It is not required that the reference cell be linear, and there are no restrictions on the shape of the spectral response curve of the cell; however, temperature control of the cell within ± 1 K is recommended.

Annex F
(informative)

AM0 solar spectral irradiance

Wavelength µm	Irradiance $W \cdot m^{-2}$
0,199 5	5
0,200 5	7
0,201 5	7
0,202 5	8
0,203 5	9
0,204 5	9
0,205 5	10
0,206 5	10
0,207 5	11
0,208 5	15
0,209 5	24
0,210 5	28
0,211 5	34
0,212 5	30
0,213 5	32
0,214 5	41
0,215 5	37
0,216 5	34
0,217 5	36
0,218 5	45
0,219 5	48
0,220 5	48
0,221 5	39
0,222 5	51
0,223 5	66
0,224 5	58
0,225 5	54
0,226 5	41
0,227 5	41
0,228 5	54
0,229 5	48
0,230 5	56
0,231 5	50
0,232 5	55
0,233 5	46
0,234 5	39
0,235 5	57
0,236 5	49
0,237 5	53
0,238 5	42
0,239 5	46
0,240 5	43
0,241 5	52
0,242 5	72
0,243 5	65
0,244 5	62
0,245 5	51
0,246 5	51
0,247 5	57
0,248 5	45
0,249 5	58
0,250 5	59
0,251 5	47
0,252 5	44
0,253 5	55
0,254 5	61
0,255 5	89
0,256 5	107
0,257 5	129
0,258 5	134
0,259 5	108
0,260 5	102
0,261 5	103
0,262 5	121
0,263 5	175
0,264 5	274
0,265 5	280
0,266 5	260
0,267 5	270
0,268 5	260
0,269 5	252
0,270 5	293
0,271 5	232
0,272 5	215
0,273 5	204
0,274 5	137
0,275 5	200
0,276 5	258
0,277 5	240
0,278 5	166
0,279 5	89
0,280 5	112
0,281 5	231
0,282 5	307
0,283 5	330
0,284 5	244
0,285 5	141
0,286 5	320
0,287 5	371
0,288 5	307
0,289 5	456
0,290 5	623
0,291 5	600
0,292 5	545
0,293 5	545
0,294 5	509
0,295 5	548
0,296 5	492
0,297 5	531
0,298 5	413
0,299 5	485
0,300 5	403

Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}
0,301 5	445	0,322 4	773	0,349 5	865
0,302 5	484	0,322 8	758	0,350 5	1 119
0,303 5	631	0,323 2	646	0,351 5	993
0,304 5	610	0,323 6	603	0,352 5	871
0,305 5	580	0,324	604	0,353 5	1 115
0,306 5	575	0,324 4	618	0,354 5	1 133
0,307 5	645	0,324 8	654	0,355 5	1 058
0,308 5	613	0,325 2	646	0,356 5	938
0,309 5	484	0,325 6	682	0,357 5	891
0,31	495	0,326	852	0,358 5	627
0,310 4	507	0,326 4	1 049	0,359 5	1 136
0,310 8	588	0,326 8	1 111	0,360 5	979
0,311 2	707	0,327 2	1 108	0,361 5	894
0,311 6	747	0,327 6	1 050	0,362 5	1 175
0,312	707	0,328	965	0,363 5	958
0,312 4	644	0,328 4	914	0,364 5	1 015
0,312 8	663	0,328 8	913	0,365 5	1 263
0,313 2	710	0,329 2	952	0,366 5	1 249
0,313 6	691	0,329 6	1 043	0,367 5	1 214
0,314	689	0,33	1 144	0,368 5	1 088
0,314 4	722	0,330 4	1 137	0,369 5	1 331
0,314 8	673	0,330 5	1 006	0,370 5	1 075
0,315 2	695	0,331 5	968	0,371 5	1 307
0,315 6	765	0,332 5	921	0,372 5	1 065
0,316	675	0,333 5	905	0,373 5	838
0,316 4	569	0,334 5	940	0,374 5	878
0,316 8	623	0,335 5	982	0,375 5	1 141
0,317 2	749	0,336 5	765	0,376 5	1 101
0,317 6	830	0,337 5	866	0,377 5	1 291
0,318	813	0,338 5	916	0,378 5	1 341
0,318 4	673	0,339 5	937	0,379 5	1 000
0,318 8	642	0,340 5	992	0,380 5	1 289
0,319 2	768	0,341 5	936	0,381 5	1 096
0,319 6	759	0,342 5	995	0,382 5	733
0,32	712	0,343 5	985	0,383 5	684
0,320 4	778	0,344 5	719	0,384 5	1 027
0,320 8	844	0,345 5	967	0,385 5	954
0,321 2	847	0,346 5	919	0,386 5	1 071
0,321 6	736	0,347 5	902	0,387 5	966
0,322	695	0,348 5	948	0,388 5	912

Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}
0,389 5	1 227	0,429 5	1 477	0,469 5	1 992
0,390 5	1 223	0,430 5	1 136	0,470 5	1 879
0,391 5	1 398	0,431 5	1 688	0,471 5	2 020
0,392 5	955	0,432 5	1 648	0,472 5	2 043
0,393 5	489	0,433 5	1 733	0,473 5	1 993
0,3945	1 101	0,434 5	1 672	0,474 5	2 053
0,395 5	1 378	0,435 5	1 725	0,475 5	2 018
0,396 5	650	0,436 5	1 931	0,476 5	1 958
0,397 5	1 040	0,437 5	1 808	0,477 5	2 077
0,398 5	1 538	0,438 5	1 569	0,478 5	2 011
0,399 5	1 655	0,439 5	1 827	0,479 5	2 078
0,400 5	1 649	0,440 5	1 715	0,480 5	2 037
0,401 5	1 796	0,441 5	1 933	0,481 5	2 092
0,402 5	1 803	0,442 5	1 982	0,482 5	2 025
0,403 5	1 658	0,443 5	1 911	0,483 5	2 021
0,404 5	1 602	0,444 5	1 975	0,484 5	1 971
0,405 5	1 672	0,445 5	1 823	0,485 5	1 832
0,406 5	1 624	0,446 5	1 893	0,486 5	1 627
0,407 5	1 545	0,447 5	2 079	0,487 5	1 832
0,408 5	1 824	0,448 5	1 975	0,488 5	1 916
0,409 5	1 706	0,449 5	2 029	0,489 5	1 962
0,410 5	1 502	0,450 5	2 146	0,490 5	2 009
0,411 5	1 819	0,451 5	2 111	0,491 5	1 898
0,412 5	1 791	0,452 5	1 943	0,492 5	1 898
0,413 5	1 758	0,453 5	1 972	0,493 5	1 890
0,414 5	1 739	0,454 5	1 981	0,494 5	2060
0,415 5	1 736	0,455 5	2 036	0,495 5	1 928
0,416 5	1 844	0,456 5	2 079	0,496 5	2 019
0,417 5	1 667	0,457 5	2 102	0,497 5	2 020
0,418 5	1 686	0,458 5	1 973	0,498 5	1 868
0,419 5	1 703	0,459 5	2 011	0,499 5	1 972
0,420 5	1 760	0,460 5	2 042	0,500 5	1 859
0,421 5	1 799	0,461 5	2 057	0,501 5	1 814
0,422 5	1 584	0,462 5	2 106	0,502 5	1 896
0,423 5	1 713	0,463 5	2 042	0,503 5	1 936
0,424 5	1 770	0,464 5	1 978	0,504 5	1 871
0,425 5	1 697	0,465 5	2 044	0,505 5	1 995
0,426 5	1 700	0,466 5	1 923	0,506 5	1 963
0,427 5	1 571	0,467 5	2 017	0,507 5	1 908
0,428 5	1 589	0,468 5	1 996	0,508 5	1 921

Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}
0,509 5	1 918	0,549 5	1 897	0,589 5	1 614
0,510 5	1 949	0,550 5	1 864	0,590 5	1 815
0,511 5	1 999	0,551 5	1 873	0,591 5	1 789
0,512 5	1 869	0,552 5	1 848	0,592 5	1 810
0,513 5	1 863	0,553 5	1 884	0,593 5	1 798
0,514 5	1 876	0,554 5	1 900	0,594 5	1 776
0,515 5	1 902	0,555 5	1 899	0,595 5	1 785
0,516 5	1 671	0,556 5	1 823	0,596 5	1 807
0,517 5	1 728	0,557 5	1 848	0,597 5	1 783
0,518 5	1 656	0,558 5	1 789	0,598 5	1 760
0,519 5	1 830	0,559 5	1 810	0,599 5	1 777
0,520 5	1 833	0,560 5	1 845	0,600 5	1 748
0,521 5	1 908	0,561 5	1 826	0,601 5	1 753
0,522 5	1 825	0,562 5	1 852	0,602 5	1 721
0,523 5	1 896	0,563 5	1 863	0,603 5	1 789
0,524 5	1 960	0,564 5	1 856	0,604 5	1 779
0,525 5	1 932	0,565 5	1 800	0,605 5	1 766
0,526 5	1 676	0,566 5	1 831	0,606 5	1 762
0,527 5	1 830	0,567 5	1 889	0,607 5	1 760
0,528 5	1 899	0,568 5	1 812	0,608 5	1 745
0,529 5	1 920	0,569 5	1 862	0,609 5	1 746
0,530 5	1 954	0,570 5	1 772	0,610 5	1 705
0,531 5	1 965	0,571 5	1 825	0,611 5	1 748
0,532 5	1 773	0,572 5	1 894	0,612 5	1 707
0,533 5	1 925	0,573 5	1 878	0,613 5	1 685
0,534 5	1 860	0,574 5	1 869	0,614 5	1 715
0,535 5	1 992	0,575 5	1 832	0,615 5	1 715
0,536 5	1 873	0,576 5	1 848	0,616 5	1 611
0,537 5	1 884	0,577 5	1 859	0,617 5	1 709
0,538 5	1 906	0,578 5	1 786	0,618 5	1 726
0,539 5	1 834	0,579 5	1 830	0,619 5	1 709
0,540 5	1 772	0,580 5	1 840	0,620 5	1 736
0,541 5	1 883	0,581 5	1 855	0,621 5	1 692
0,542 5	1 827	0,582 5	1 875	0,622 5	1 715
0,543 5	1 881	0,583 5	1 859	0,623 5	1 668
0,544 5	1 881	0,584 5	1 862	0,624 5	1 658
0,545 5	1 903	0,585 5	1 786	0,625 5	1 634
0,546 5	1 881	0,586 5	1 832	0,626 5	1 699
0,547 5	1 835	0,587 5	1 850	0,627 5	1 699
0,548 5	1 865	0,588 5	1 752	0,628 5	1 699

Wavelength µm	Irradiance $\text{W}\cdot\text{m}^{-2}$
0,629 5	1 679
0,631	1 641
0,633	1 653
0,635	1 658
0,637	1 656
0,639	1 653
0,641	1 616
0,643	1 623
0,645	1 629
0,647	1 605
0,649	1 560
0,651	1 608
0,653	1 601
0,655	1 534
0,657	1 386
0,659	1 551
0,661	1 573
0,663	1 557
0,665	1 562
0,667	1 537
0,669	1 548
0,671	1 518
0,673	1 523
0,675	1 512
0,677	1 510
0,679	1 500
0,681	1 494
0,683	1 481
0,685	1 457
0,687	1 469
0,689	1 463
0,691	1 450
0,693	1 450
0,695	1 438
0,697	1 418
0,699	1 427
0,701	1 388
0,703	1 390
0,705	1 417
0,707	1 402
0,709	1 386
0,711	1 387
0,713	1 375
0,715	1 368
0,717	1 355
0,719	1 329
0,721	1 332
0,723	1 349
0,725	1 351
0,727	1 347
0,729	1 320
0,731	1 327
0,733	1 319
0,735	1 310
0,737	1 308
0,739	1 279
0,741	1 259
0,743	1 287
0,745	1 280
0,747	1 284
0,749	1 271
0,751	1 263
0,753	1 260
0,755	1 256
0,757	1 249
0,759	1 241
0,761	1 238
0,763	1 242
0,765	1 222
0,767	1 186
0,769	1 204
0,771	1 205
0,773	1 209
0,775	1 189
0,777	1 197
0,779	1 188
0,781	1 188
0,783	1 177
0,785	1 181
0,787	1 178
0,789	1 175
0,791	1 159
0,793	1 144
0,795	1 135
0,797	1 153
0,799	1 136
0,801	1 143
0,803	1 130
0,805	1 116
0,807	1 121
0,809	1 096
0,811	1 115
0,813	1 116
0,815	1 108
0,817	1 105
0,819	1 065
0,821	1 081
0,823	1 074
0,825	1 076
0,827	1 077
0,829	1 073
0,831	1 069
0,833	1 034
0,835	1 053
0,837	1 052
0,839	1 042
0,841	1 045
0,843	1 028
0,845	1 033
0,847	1 025
0,849	971
0,851	1 003
0,853	973
0,855	877
0,857	1 011
0,859	997
0,861	997
0,863	999
0,865	970
0,867	880

Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}	Wavelength µm	Irradiance W·m^{-2}
0,869	967	0,949	777	1,072 5	638
0,871	986	0,951	778	1,077 5	630
0,873	978	0,953	771	1,082 5	620
0,875	981	0,955	760	1,087 5	614
0,877	984	0,957	774	1,092 5	612
0,879	959	0,959	771	1,097 5	599
0,881	960	0,961	767	1,102 5	608
0,883	948	0,963	767	1,107 5	601
0,885	963	0,965	764	1,112 5	603
0,887	947	0,967	757	1,117 5	589
0,889	949	0,969	776	1,122 5	579
0,891	944	0,971	763	1,127 5	569
0,893	934	0,973	764	1,132 5	566
0,895	936	0,975	750	1,137 5	563
0,897	939	0,977	768	1,142 5	557
0,899	912	0,979	768	1,147 5	556
0,901	905	0,981	762	1,152 5	545
0,903	905	0,983	766	1,157 5	554
0,905	893	0,985	771	1,162 5	540
0,907	891	0,987	756	1,167 5	530
0,909	861	0,989	767	1,172 5	533
0,911	870	0,991	764	1,177 5	525
0,913	876	0,993	755	1,182 5	514
0,915	866	0,995	756	1,187 5	512
0,917	859	0,997	743	1,192 5	511
0,919	858	0,999	743	1,197 5	502
0,921	830	1,002 5	745	1,202 5	496
0,923	821	1,007 5	737	1,207 5	494
0,925	825	1,012 5	734	1,212 5	489
0,927	828	1,017 5	721	1,217 5	500
0,929	833	1,022 5	704	1,222 5	481
0,931	826	1,027 5	708	1,227 5	481
0,933	832	1,032 5	688	1,232 5	484
0,935	818	1,037 5	692	1,237 5	477
0,937	802	1,042 5	681	1,242 5	477
0,939	808	1,047 5	685	1,247 5	466
0,941	800	1,052 5	661	1,252 5	474
0,943	784	1,057 5	650	1,257 5	463
0,945	799	1,062 5	642	1,262 5	444
0,947	793	1,067 5	643	1,267 5	438

Wavelength µm	Irradiance W·m^{-2}
1,272 5	439
1,277 5	453
1,282 5	435
1,287 5	437
1,292 5	442
1,297 5	438
1,302 5	438
1,307 5	429
1,312 5	419
1,317 5	416
1,322 5	416
1,327 5	411
1,332 5	405
1,337 5	400
1,342 5	398
1,347 5	394
1,352 5	387
1,357 5	382
1,362 5	378
1,367 5	370
1,372 5	369
1,377 5	368
1,382 5	364
1,387 5	364
1,392 5	358
1,397 5	357
1,402 5	353
1,407 5	350
1,412 5	346
1,417 5	344
1,422 5	343
1,427 5	348
1,432 5	337
1,437 5	331
1,442 5	327
1,447 5	318
1,452 5	323
1,457 5	307
1,462 5	317
1,467 5	311
1,472 5	311
1,477 5	307
1,482 5	303
1,487 5	298
1,492 5	303
1,497 5	300
1,502 5	296
1,507 5	295
1,512 5	290
1,517 5	290
1,522 5	286
1,527 5	290
1,532 5	282
1,537 5	274
1,542 5	275
1,547 5	274
1,552 5	273
1,557 5	272
1,562 5	269
1,567 5	263
1,572 5	260
1,577 5	259
1,582 5	255
1,587 5	252
1,592 5	246
1,597 5	246
1,602 5	247
1,607 5	242
1,612 5	244
1,617 5	243
1,622 5	240
1,627 5	244
1,632 5	241
1,637 5	237
1,642 5	234
1,647 5	235
1,652 5	234
1,657 5	234
1,662 5	233
1,667 5	229
1,672 5	228
1,677 5	220
1,682 5	221
1,687 5	219
1,692 5	219
1,697 5	214
1,702 5	217
1,707 5	212
1,712 5	203
1,717 5	212
1,722 5	205
1,727 5	196
1,732 5	190
1,737 5	189
1,742 5	191
1,747 5	185
1,752 5	187
1,757 5	189
1,762 5	184
1,767 5	182
1,772 5	177
1,777 5	173
1,782 5	171
1,787 5	170
1,792 5	169
1,797 5	173
1,802 5	169
1,807 5	168
1,812 5	160
1,817 5	160
1,822 5	159
1,827 5	156
1,832 5	156
1,837 5	150
1,842 5	153
1,847 5	151
1,852 5	148
1,857 5	145
1,862 5	143
1,867 5	143

Wavelength µm	Irradiance W·m^{-2}
1,872 5	135
1,877 5	135
1,882 5	140
1,887 5	138
1,892 5	137
1,897 5	138
1,902 5	133
1,907 5	136
1,912 5	138
1,917 5	136
1,922 5	134
1,927 5	132
1,932 5	132
1,937 5	131
1,942 5	129
1,947 5	127
1,952 5	126
1,957 5	122
1,962 5	126
1,967 5	125
1,972 5	125
1,977 5	129
1,982 5	125
1,987 5	123
1,992 5	121
1,997 5	123
2,002 5	116
2,012 5	114
2,022 5	113
2,032 5	110
2,042 5	107
2,052 5	104
2,062 5	100
2,077 5	101
2,092 5	98
2,107 5	93
2,122 5	87
2,137 5	85
2,152 5	81
2,167 5	80
2,182 5	75
2,197 5	73
2,212 5	75
2,227 5	75
2,247 5	72
2,262 5	71
2,282 5	69
2,302 5	66
2,322 5	53
2,342 5	58
2,362 5	65
2,382 5	55
2,402 5	54
2,422 5	57
2,442 5	51
2,467 5	53
2,492 5	54
2,517 5	47
2,542 5	46
2,567 5	44
2,592 5	42
2,617 5	41
2,642 5	39
2,672 5	38
2,702 5	36
2,732 5	35
2,762 5	34
2,797 5	32
2,832 5	31
2,867 5	29
2,907 5	28
2,947 5	26
2,987 5	25
3,025	24
3,075	23
3,125	21
3,175	20
3,235	19
3,295	18
3,355	16
3,425	15
3,495	14
3,575	13
3,665	12
3,755	11
3,855	10
3,965	9
4,085	8
4,225	7
4,385	6
4,575	5
4,805	4
5,085	3
5,445	2
5,925	2
6,615	1
7,785	1
10,075	0,2

Annex G
(normative)

Solar simulator performance requirements

G.1 General

This annex gives the requirements for solar simulators used for indoor testing of space solar cells in conjunction with a spectrally matched AM0 standard solar cell. The output of a solar cell is a strong function of the wavelength of incident spectral irradiance distribution. To reduce measurement errors, this International Standard specifies the acceptable match to the AM0 reference solar spectral irradiance distribution, but it should be noted that the magnitude of the error is also affected by the spectral response mismatch between the AM0 standard solar cell and the test specimen.

G.2 Type of simulators

Two types of solar simulators are commercially available for solar cell performance testing. The "steady-state" type of, for example, filtered xenon, dichroic filtered tungsten or modified mercury vapour with tungsten electrodes, is suitable for single cells and small modules. The pulsed type, consisting of one or two long-arc xenon flash lamps, is better for large modules as it can irradiate large areas uniformly. Another advantage of this type is that there is negligible heat input to the test cells, so that they remain uniformly at the ambient temperature, which can be easily and accurately measured. The pulse-forming network and the data acquisition and processing equipment are generally supplied as part of the simulator.

G.3 Solar simulator requirements

G.3.1 Total irradiance

The solar simulator shall be capable of producing the standard irradiance of 1 367 $\mathrm{W \cdot m^{-2}}$ (as measured with an AM0 standard solar cell) at the test plane and higher or lower irradiances as may be required.

G.3.2 Spectral match

The spectral irradiance distribution of the solar simulator shall match the AM0 solar spectral irradiance to the extent indicated for the relevant class of simulator in Table G.1 and must cover the spectrum relative to the band gap of the test cell.

G.3.3 Uniformity

The irradiance in the test plane over the full extent of the nominated test area, as measured with a suitable detector(s), shall be uniform to the degree specified for the relevant class of simulator in Table G.1.

For single cell and subassembly testing, the largest dimension of the detector shall be less than half of the smallest dimension of the cell. In the case of a module, the detector shall be no bigger than a single component cell.

$$\text{Nonconformity (\%)} = \pm \frac{\text{maximum irradiance} - \text{minimum irradiance}}{\text{maximum irradiance} + \text{minimum irradiance}} \times 100$$

where maximum and minimum irradiance are those measured with the detector(s) over the nominated test area (corrected for temporal instability).

G.3.4 Temporal stability

During the time of data acquisition, the irradiance shall be stable to the degree specified for the relevant class of simulator in Table G.1.

$$\text{Temporal instability (\%)} = \pm \frac{\text{maximum irradiance} - \text{minimum irradiance}}{\text{maximum irradiance} + \text{minimum irradiance}} \times 100$$

where maximum and minimum irradiance are those measured with the detector at any particular point on the test plane during the time of data acquisition.

NOTE For the special case of pulsed simulators, the temporal stability requirements apply only to the irradiance levels present during the actual measurement of each data point. The light source is collimated to within a 2,5° half angle or less.

G.3.5 Characteristics check

The characteristics described in subclause G.3.1 to G.3.4 shall be checked whenever there is any change in Class A or B simulators (including aging) which could affect these characteristics beyond acceptable limits. The detectors used shall have an angle of view sufficient to accept the entire incident light at any point on the test plane.

G.4 Data sheet

The following information shall be recorded on a data sheet that shall accompany each simulator:

- Date of issue of data sheet,
- Date of measurement,
- Manufacturer,
- Type,
- Class (determined by the lowest classification of an individual characteristic),
- Location of test plane,
- Nominal lamp current,
- Nominal irradiance,
- Spectral irradiance distribution,
- Nonuniformity of irradiance over the nominated area,
- Maximum angle subtended by the light source (including reflected light) at any point on the test plane (collimation),
- Temporal stability,
- For pulsed simulators, characteristics of the pulse,
- For pulsed simulators, the time intervals between data points.

Table G.1 — Solar Simulator Classification

Characteristics	Spectral region µm	Class A %	Class B %	Class C %
Spectral mismatch	0,30 to 0,50	± 20	± 30	± 40
	0,50 to 0,80	± 10	± 20	± 30
	0,80 to 1,20	± 10	± 20	± 30
Non-uniformity of irradiance		⩽ ± 2	⩽ ± 5	⩽ ± 10
Temporal stability		⩽ ± 1	⩽ ± 5	⩽ ± 10

Table G.2 — AM0 Solar Spectral Irradiance[1)]

Wavelength µm	Integrated irradiance [a] $W \cdot m^{-2}$	Percentage %
⩾ 0,30 to ⩽ 0,40	93,27	8,8
⩾ 0,40 to ⩽ 0,50	186,56	17,6
⩾ 0,50 to ⩽ 0,60	185,61	17,6
⩾ 0,60 to ⩽ 0,70	158,30	15,0
⩾ 0,70 to ⩽ 0,80	127,41	12,0
⩾ 0,80 to ⩽ 0,90	101,57	9,6
⩾ 0,90 to ⩽ 1,00	80,15	7,6
⩾ 1,00 to ⩽ 1,20	122,02	11,5
⩾ 0,30 to ⩽ 1,20	1054,89	100,0

[a] In accordance with the AM0 solar spectral irradiance given in Annex E.

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1) Distribution curve given in Figure 4.

Annex H
(normative)

Measurement method of the spectral irradiance

H.1 General

This annex specifies the methods of spectral irradiance measurement for light.

H.2 Terms and definition

The definitions and terms used in this annex shall comply with the following:

H.2.1
centroidal wavelength
wavelength that represents the band, this characteristic applying to input optics having a band sensitivity to wavelength

NOTE The centroidal wavelength, λ_g, may be calculated from the following equation:

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

where

λ_g is the centroidal wavelength (nm);

λ is the wavelength (nm);

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

H.2.2
wavelength width of slit
effect of the transmission wavelength band on the spectroradiometer

NOTE The relation between the mechanical width of the entrance slit and the wavelength width of the entrance slit is calculated from the following equation:

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

where

b_i is the wavelength width of the entrance slit (nm);

w_i is the mechanical width of the entrance slit (mm).

$d\theta_i/d\lambda$ is the degree of dispersion of input side (rad/nm);

f_i is the focal length of collimator (mm).

The relation between the mechanical width of the exit slit and the wavelength width of the exit slit is calculated from the following equation:

$$b_\mathrm{o} = \frac{w_\mathrm{o}}{f_\mathrm{o}\dfrac{d\theta_\mathrm{o}}{d\lambda}}$$

where

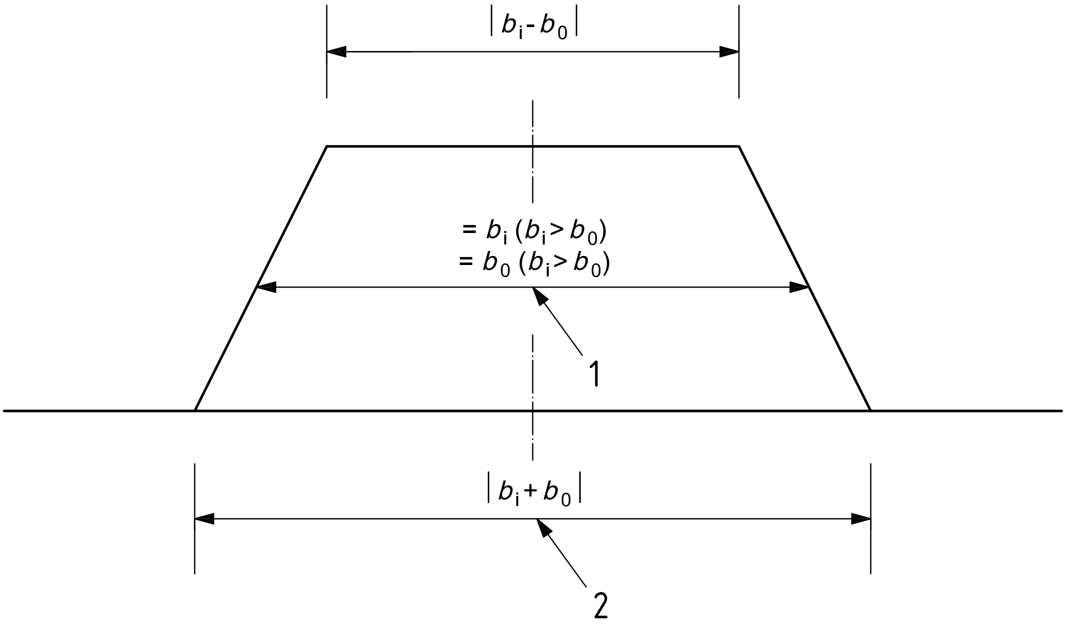
b_o is the wavelength width of exit slit (nm);

w_o is the mechanical width of exit slit (mm);

$d\theta_\mathrm{o}/d\lambda$ is the degree of dispersion of exit side (rad/nm);

f_o is the local length of input optics (mm).

The transmission characteristics and wavelength width of the monochromator are shown in Figure H.1.



Key

1 wavelength width

2 wavelength

Figure H.1 — Transmission characteristics

H.3 Measurement method of the spectral irradiance

H.3.1 Principle of measurement

The spectral irradiance shall be measured by the method in which the sample light is compared with the standard lamp for each wavelength.

H.3.2 Standard lamp

A source of calibrated spectral irradiance is needed in order to measure the spectral irradiance of a solar simulator. The term standard lamp has several meanings and may have calibrated spectral irradiance or calibrated total radiance values. For the purpose of solar cell calibration and measurement, we define a standard lamp as a calibrated source of spectral irradiance.

The required features of a standard lamp used for single junction solar cell calibration are:

— wavelength range	0,25 µm to 2,5 µm
— traceability	calibration traceable to a national standards laboratory
— stability	output to vary less than 1 % through 50 h of use.
— operation	operated in the manner prescribed by the manufacturer

The requirements of spectral range and stability usually lead to a choice of a quartz-halogen, tungsten filament lamp. The higher operating temperature allows increased low wavelength (blue) irradiance, while the halogen effect increase the stability of the lamp.

The standard lamp shall be a spectral irradiance lamp with the value measured by an accredited laboratory.

NOTE 1 The value of spectral irradiance standard lamp is based on the standard established by the following national organizations:

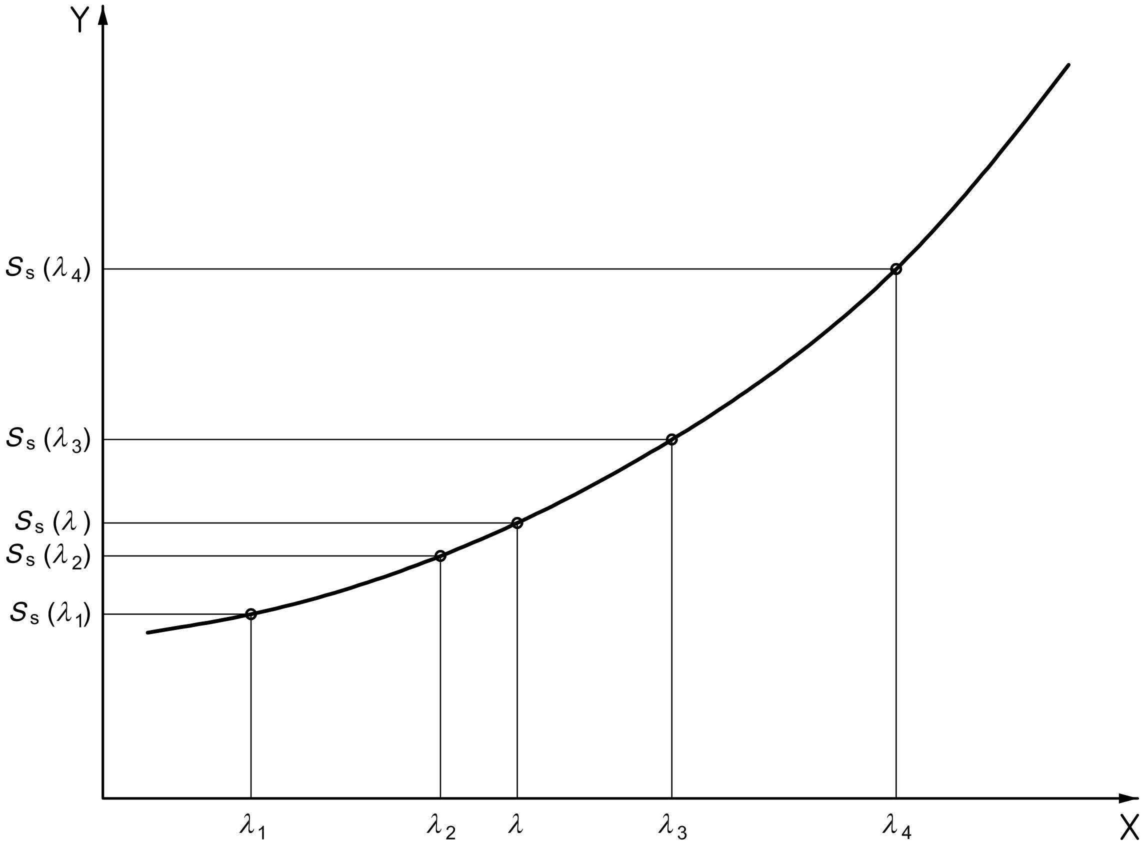
CSIRO	Commonwealth Scientific and Industrial Research Organization, Division of Applied Physics, Lindfield, Australia
AIST	National Institute of Advanced Industrial Science and Technology, Ibaraki, Japan
INM	Institut National de Métrologie du Conservatoire National des Arts et Métiers, Paris, France
IOM	Instituto de Optica Daza de Valdes, Madrid, Spain
NIM	National Institute of Metrology, Beijing, China
NIST	National Institute of Standards and Technology, Gaithersburg, MD, USA
NPL	National Physical Laboratory, Teddington, Middlesex, UK
DPT	Division of Production Technology, CSIR, Pretoria, South Africa
NRC	National Research Council, Ottawa, Canada
OMH	National Office of Measures, Budapest, Hungary
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
VNIIOFI	All-Union Research Institute of Optical and Physical Measurements, Moscow, Russia

NOTE 2 The spectral irradiance of the standard lamp is given at discrete wavelengths, so that the spectral irradiance $S_s(\lambda)$ at the intermediate wavelength λ shall be calculated from the following interpolation formula, using the value at the upper two and lower two wavelengths (see Figure H.2):

$$S_s(\lambda)=\frac{(\lambda-\lambda_2)(\lambda-\lambda_3)(\lambda-\lambda_4)}{(\lambda_1-\lambda_2)(\lambda_1-\lambda_3)(\lambda_1-\lambda_4)}S_s(\lambda_1)+\frac{(\lambda-\lambda_1)(\lambda-\lambda_3)(\lambda-\lambda_4)}{(\lambda_2-\lambda_1)(\lambda_2-\lambda_3)(\lambda_2-\lambda_4)}S_s(\lambda_2)$$
$$+\frac{(\lambda-\lambda_1)(\lambda-\lambda_2)(\lambda-\lambda_4)}{(\lambda_3-\lambda_1)(\lambda_3-\lambda_2)(\lambda_3-\lambda_4)}S_s(\lambda_3)+\frac{(\lambda-\lambda_1)(\lambda-\lambda_2)(\lambda-\lambda_3)}{(\lambda_4-\lambda_1)(\lambda_4-\lambda_2)(\lambda_4-\lambda_3)}S_s(\lambda_4)$$

where

$S_s(\lambda)$	is the spectral distribution at wavelength λ of a standard lamp;
λ_1, λ_2, λ_3, λ_4	are the wavelengths at which spectral irradiance is given (assuming $\lambda_1 < \lambda_2 < \lambda_3 < \lambda_4$);
$S_s(\lambda_1)$, $S_s(\lambda_2)$, $S_s(\lambda_3)$, $S_s(\lambda_4)$	are the spectral irradiance given at wavelength λ_1, λ_2, λ_3 et λ_4, respectively.



Key

X Wavelength

Y Spectral irradiance

Figure H.2 — Interpolation of the spectral irradiance for the standard lamp

H.3.3 Performance of the spectroradiometer

The performance of the spectroradiometer shall fulfil the following conditions.

a) Wavelength scale

In the case of the spectroradiometer, the difference between the indicated wavelength of the spectroradiometer and the centroidal wavelength shall be not more than 0,5 nm.

b) Photometric scale

The accuracy and repeatability of the ratio of the outputs to the incident lights of 2 to 1 intensity ratio shall be not more than 0,5 % and 0,2 % of the respective values. Further, the accuracy and repeatability of the ratio of the outputs to the incident lights of 10 to 1 intensity ratio shall be not more than 1 % and 0,5 % of the respective values.

c) Stray Light

The output from the stray light, when an incandescent lamp is used as the light source, the spectroradiometer is set at 450 nm wavelength, and a sharp-cut glass filter with the transmission wavelength limits of 500 nm ± 5 nm is placed across the incident light path, shall be not more than 1 % of the output when the filter is not in place.

H.3.4 Input optics for spectroradiometer

The light of the standard lamp and the sample light shall irradiate the dispersing element (prism, diffraction grating, etc.) of the monochromator under the same geometrical condition, which shall be one of the following conditions.

a) Condition A: Apply the source light perpendicularly on a reflecting diffuser made of barium sulfate or the like and introduce the reflected and diffused lights in a direction 45° from the normal to the reflector into the monochromator directly or through an optical system (Figure H.3).

b) Condition B: Apply the light on a diffuse transmission surface of a glass plate made by grinding with abrasives of No. 100 to No. 200 and introduce the diffused transmission light directly into the monochromator (Figure H.4).

c) Condition C: Let the light into an integrating sphere and introduce the diffused light from the sphere into the monochromator directly or through an optical system (Figure H.5).

H.3.5 Conditions of conducting measurement for spectral irradiance

The measurement of spectral irradiance shall be conducted in accordance with the following conditions:

a) Wavelength width of slit: The wavelength width of entrance and exit slit of spectroradiometer shall be 5 nm or the integral quotient thereof at 546,1 nm in wavelength.

b) Wavelength interval: The wavelength interval at which the spectral irradiance is to be measured shall be equal to the wavelength width of slit or the integral quotient thereof.

H.3.6 Method of calculation for spectral irradiance

The spectral irradiance $S_t(\lambda)$ shall be calculated from the following equation:

$$S_t(\lambda) = \frac{R_t(\lambda)}{R_s(\lambda)} S_s(\lambda)$$

where

$S_s(\lambda)$ is the spectral irradiance at wavelength λ for standard lamp;

$R_t(\lambda)$ is the reading of spectroradiometer at wavelength λ for sample light;

$R_s(\lambda)$ is the reading of spectroradiometer at wavelength λ for standard lamp;

λ is the wavelength of the spectroradiometer.

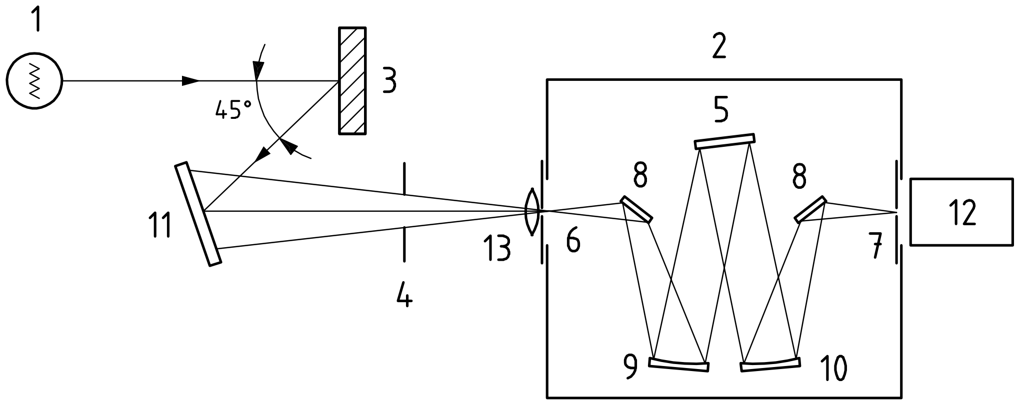


Figure H.3 — Input optics of condition A

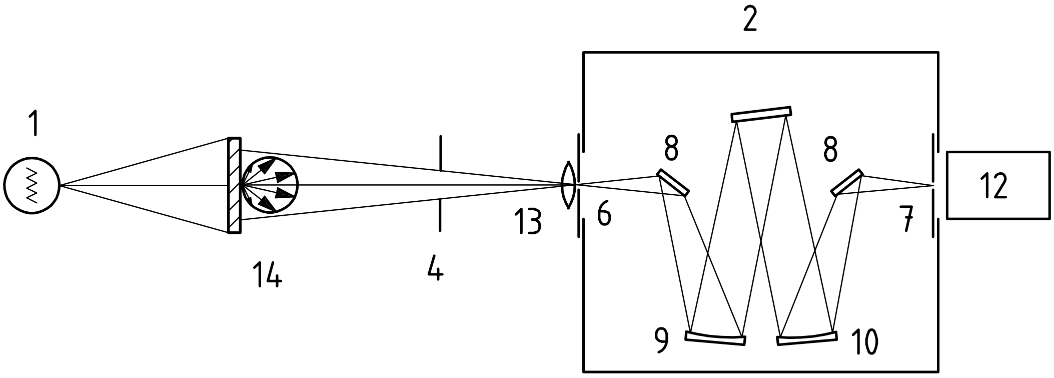


Figure H.4 — Input optics of condition B

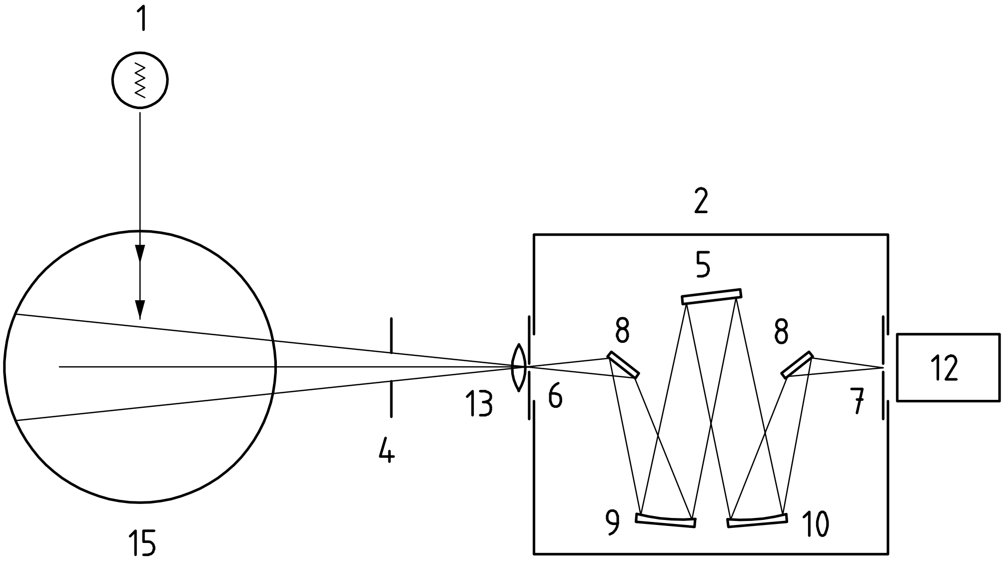


Figure H.5 — Input optics of condition C

Item List			
Item Number	**Description**	**Item Number**	**Description**
1	Light source	9	Collimator mirror
2	Monochromator	10	Focusing mirror
3	Reflecting diffuser	11	Reflecting mirror
4	Diaphragm	12	Detector
5	Diffraction grating	13	Field lens
6	Entrance slit	14	Diffuse transmission surface
7	Exit slit	15	Integrating sphere
8	Flat mirror	–	–

Annex I
(normative)

Linearity measurement methods

I.1 General

This annex describes procedures for determining the degree of linearity of any solar cell parameter with respect to a test parameter. It is primarily intended for use by calibration laboratories, cell manufacturers and system designers. It applies to all solar cells and is intended to be carried out on a sample or on a comparable cell of identical technology. It is to be performed prior to all measurement and correction procedures that require a linear cell.

The methodology used in this International Standard is similar to that specified in Annex D in which a linear (straight-line) function is fitted to a set of data points using a least-squares fit calculation routine. The variation of the data from this function is also calculated, and the definition of linearity is expressed as an allowable variation percentage.

A cell is considered linear when the following conditions are met over the temperature and irradiance range of interest; ideally, this range of temperature should be 25 °C to 100 °C minimum, and an irradiance range of 1 000 $W \cdot m^{-2}$ to 1 367 $W \cdot m^{-2}$ minimum.

a) The variation of the slope of short circuit to irradiance remains constant within ± 2 %.

b) The variation of the slope of open circuit voltage to the logarithm of irradiance [ln (G)] remains constant within ± 5 %.

c) The variation of the slope of short-circuit current and open circuit voltage to cell temperature remains constant within ± 10 %.

d) The variation of relative spectral response at a specified voltage is less than 5 % for the wavelength band of interest.

I.2 Apparatus

I.2.1 Test Apparatus

The following apparatus is required to control and measure the test conditions.

a) A radiant source (solar simulator, class B or better in accordance with Annex F) of the type to be used in subsequent tests.

b) Any equipment necessary to change the irradiance over the range of interest without affecting the relative spectral irradiance distribution such as mesh filters or neutral density filters.

c) An AM0 standard cell in conformance with Clause 8, and linear in short-circuit current over the irradiance range of interest to ± 1 %

d) Any equipment necessary to change the temperature of the test specimen over the range of interest.

e) A means for controlling the temperature of the test specimen and standard cell, or a removable shade.

f) A suitable mount for supporting the test specimen and the standard cell in the same plane normal to the radiant source.

g) Means for monitoring the temperature of the test specimen and standard cell to an accuracy of ± 1 %, and repeatability to ± 0,5 °C.

I.2.2 Specimen Apparatus

Depending on the performance parameter for which the linearity determination is being made, one or more of the following apparatus items may be required.

a) Equipment for measuring the current of the test specimen and standard cell to an accuracy of ± 0,1 % of the reading.

b) Equipment for measuring the voltage of the test specimen and standard cell to an accuracy of ± 0,1 % of the reading.

c) Equipment for measuring the relative spectral response of the test specimen (or a respective sample equivalent to the test specimen) in accordance with Annex C to an accuracy of ± 2 % of the reading.

I.3 Procedure for current and voltage linearity test with a solar simulator

a) Mount the test specimen and the standard cell coplanar in the test plane of the simulator so that both are normal to the centerline of the beam within ± 2°. Connect to the necessary instrumentation.

b) If the test specimen and standard cell are equipped with temperature controls, set the controls at the desired level. If temperature controls are not used, allow the test specimen and standard cell to stabilize within ± 1 °C of the room air temperature.

c) Set the irradiance at the test plane to the upper limit of the range of interest by using the standard cell measured current (I_{sc}) and its calibration value at STC (I_{rc}).

d) Conduct the test and take simultaneous readings of the test parameter X, the test specimen cell parameter Y and the temperature and short-circuit current of the standard cell. For example, if the linearity of short-circuit current versus irradiance were being determined, X would be the irradiance and Y would be the short-circuit of the test specimen.

e) The irradiance G_0, shall be calculated in accordance with Annex E from the measured current (I_{sc}) of the standard cell and its calibration value at STC (I_{rc}). A correction should be applied to account for the temperature of the standard cell T_{m} with the specified temperature coefficient of the standard cell α_{rc}.

$$G_0 = (1\,000 \times I_{\mathrm{sc}})/[I_{\mathrm{rc}} - \alpha_{\mathrm{rc}}(T_{\mathrm{m}} - 25)]$$

f) If the test parameter being varied is the irradiance, reduce the irradiance on the test specimen to a known fraction without affecting the spatial uniformity or the spectral irradiance. Several methods of accomplishing this are:

  1) Increasing the distance between the test plane and the lamp. With the standard cell maintained in the same plane as the test specimen, k_i is the ratio of the standard cell short-circuit current (I_{sc}) to its calibration value (I_{rc}).

  2) Using an optical lens. In this case k_i is the ratio of the standard cell short circuit current (I_{sc}) to its calibration value (I_{rc}). Care should be exercised to assure that the lens does not significantly change the relative value in the wavelength range in which the test and standard specimens are responsive.

3) Controlling the angle of incidence. If this method is selected., the standard cell should have the same reflective properties as the test specimen and should be mounted coplanar with the test specimen. In this case k_i is the ratio of the standard cell short-circuit current (I_{sc}) to its calibration value (I_{rc}).

4) Using calibrated, uniform density mesh filters. If this method is selected, the standard cell should also be covered by the filter during the operation to enable the incident irradiance to be measured. In this case k_i is the filter calibration parameter (fraction of light transmitted).

5) Using uncalibrated, uniform density mesh filters. If this method is selected, the standard cell should also be covered by the filter during the test. In this case k_i is the ratio of the standard cell short-circuit current (I_{sc}) to its calibration value (I_{rc}).

NOTE The filter mesh opening size should be small relative to the standard cell and the test specimen (less than ± 1,0 %), to prevent a variable error that could occur because positioning.

g) Calculate the irradiance level of the test specimen G_i by using the appropriate k_i factor and the irradiance G_0 from e)

$$G_i = k_i \times G_0$$

h) If the test parameter being varied is the temperature, adjust the temperature appropriately.

i) Ensure that the test specimen and standard cell temperature remain constant to within ± 1 °C during the test.

j) Repeat d) through i). The value of the test parameter selected shall be such that the range of interest is spanned in at least four approximately equal increments. A minimum of three measurements shall be made at each of the test conditions.

I.4 Procedure for spectral response linearity test

I.4.1 General

The relative spectral response of a solar cell is measured by irradiating it by means of a narrow-bandwidth light source at a series of different wavelengths covering its response range and measuring the short-circuit current density and irradiance at each of these wavelengths. Annex C provides guidance for relative spectral response measurements.

I.4.2 Spectral considerations

a) Pre-conditioning.

   - Before the spectral response of amorphous silicon devices is measured, the device under test shall be stabilized (if necessary), as specified in the light soaking test procedure.
   - Other solar cell technologies may require different preconditioning procedures.

b) This procedure shall be applied to the full-sized test specimen if possible. If this is not possible, a small sample equivalent in construction and materials should be used.

c) Because of the effect of voltage on the relative spectral response, it is desirable to define the following terms which should be used when reporting the results:

   - Spectral response under load ($S_{\mathrm{v}\lambda}$): the current density at a particular load voltage, generated by unit irradiance at a particular wavelength (A·W^{-1}), plotted as a function of wavelength.

- Relative spectral response under load ($k_i \times S_{\mathrm{v}\lambda}$): the spectral response under load normalized to unity at wavelength of maximum response.

$$k_i \times S_{\mathrm{v}\lambda} = S_{\mathrm{v}\lambda}/S_{\mathrm{v}\lambda\ \mathrm{max}}$$

- The spectral response measurement should be done under the voltage, which is appropriate for the intended use of the spectral response data. The voltage condition, therefore, must be specified with the data.

I.4.3 General procedure

a) Set the bias voltage on the test specimen to the desired level and maintain this bias voltage within ± 3 % of V_{oc}.

b) Set the test specimen temperature to the value of interest, and maintain within ± 1 °C.

c) The spectral response measurement should be done under white bias light, similar to the AM0 solar spectral irradiance of Clause 7. Set the white bias light source irradiance to the value of interest, and maintain within ± 1 %.

d) Measure the relative spectral response over the wavelength intervals of interest. A minimum of three measurements shall be made at this condition. (See Annexes B and C.)

e) Repeat c) and d) with a new value of irradiance. The value shall be selected such that the range of interest is spanned in at least four approximately equal increments.

f) Repeat b) through e) with a new value of test specimen temperature. The value selected shall be such that the range of interest is spanned in at least four approximately equal increments.

g) If desired, this procedure may be repeated at other voltages of interest.

I.5 Linearity calculation

I.5.1 General

Verify that any variable parameters other than the one being evaluated were held constant during the testing. Small changes in temperature or irradiance may be corrected analytically to the desired condition using Annex D. This may be an iterative process, which should be updated when linearity is established and when more refined correction coefficients are determined.

I.5.2 Slope linearity determination

For performance characteristic slopes such as the open circuit voltage versus temperature, or short-circuit current versus irradiance, calculate linearity by using the following method:

a) Calculate the mean values of the test parameters, and the characteristics of the best-fit, straight line using the least-squares fit method as follows:

Step 1: Compute the mean value of the X and Y data points

$$X = \frac{\sum_{i=1}^{n} X_i}{n}$$

$$Y = \frac{\sum_{i=1}^{n} Y_i}{n}$$

where n is the number of measurements.

Step 2: Compute the slope m of the best-fit line

$$m = \frac{\sum_{i=1}^{n} (X_i - X)\, Y_i}{\sum_{i=1}^{n} (X_i - X)^2}$$

Step 3: The best-fit straight line, also known as the Regression Line, can now be written

$$Y - Y_i = m\, (X - X_i)$$

b) Compute the variation of the line slope based on the individual data point differences relative to the best-fit, straight line as follows:

Step 1: Compute the ΔY_i difference between each data point and the best fit straight line at the X_i position

$$\Delta Y_i = (Y_i - Y) - m\, (X_i - X)$$

Step 2: Compute the ΔX_i difference between each data point and the X mean

$$\Delta X_i = (X_i - X)$$

Step 3: Compute the overall slope standard deviation σ_{s} based on the above differences

$$\sigma_{\mathrm{s}} = \frac{\sum (\Delta Y_i)^2}{(n-1) \sum (\Delta X_i)^2}$$

c) The percent variation is calculated by using the best-fit straight-line slope m and the data point slope standard deviation σ_{s} as follows:

Percent variation = 100 σ_{s}/m

I.5.3 Spectral response linearity determination

The linearity of the relative spectral response of the test tube with regard to the temperature (or to the irradiance) for a fixed bias voltage is calculated using the following method:

a) Compute the mean value of the X and Y data points:

$$S_{\mathrm{r}\lambda} = \frac{\sum_{j=1}^{n} S_{\mathrm{r}\lambda j}}{n}$$

b) Calculate the $\Delta S_{\mathrm{r}\lambda j}$ differences between each $S_{\mathrm{r}\lambda j}$ data point and the $S_{\mathrm{r}\lambda}$ mean value for the given wavelength interval with fixed temperature (or irradiance)

$$\Delta S_{\mathrm{r}\lambda j} = (S_{\mathrm{r}\lambda j} - S_{\mathrm{r}\lambda})$$

c) Calculate the standard deviation σ_λ for the given wavelength interval with fixed temperature (or irradiance)

$$\sigma_\lambda = \frac{\sum (\Delta S_{\mathrm{r}\lambda j})^2}{(n-1)}$$

d) The percent variation of relative spectral response is calculated by using the wavelength band standard deviation σ_i and the mean value of relative spectral response $S_{\mathrm{r}\lambda}$ for that wavelength interval at the specified bias voltage and fixed temperature (or irradiance):

Percent variation = 100 $\sigma_i / S_{\mathrm{r}\lambda}$ (%)

e) For each wavelength interval, repeat steps a) through d):

- For each fixed temperature (with irradiance as a variable),
- For each fixed irradiance (with temperature as a variable).

f) Step a) through e) should be repeated for other bias voltages of interest.

I.5.4 Linearity requirements

When a claim is made that a given cell is linear, the applicable range of temperature, irradiance, voltage or other necessary condition shall also be stated. The requirements for the acceptable limits of non-linearity (variation) are:

a) The variation of the slope of short-circuit current density to irradiance remains constant within ± 2 %.

b) The variation of the slope of open-circuit voltage to the logarithm of irradiance [ln (G)] remains constant within ± 5 %.

c) The variation of the slope of short-circuit current density and open circuit voltage to cell temperature remains constant within ± 10 %.

d) The variation of relative spectral response at a specified voltage is less than 5 % for the wavelength band of interest.

This temperature range should be 25 °C to 60 °C with an irradiance range of 700 $\mathrm{W{\cdot}m^{-2}}$ to 1 367 $\mathrm{W{\cdot}m^{-2}}$.

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