RESULTS FROM THE 1ST INTERNATIONAL AM0 CALIBRATION ROUND ROBIN OF SILICON AND GaAs SOLAR CELLS

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ABSTRACT

AM0 solar cell calibration laboratories throughout the world are working together to create standard methods for AM0 calibration. In an effort to compare the results of different calibration methods, five different laboratories calibrated GaAs and Si solar cells. The results of this inter-comparison are presented herein.

INTRODUCTION

Calibration of solar cells is arguably the most important measurement made to characterize these devices. In this case, calibration is measuring the performance of a solar cell under one sun, air mass zero (AM0) conditions. The methods themselves are usually simple in concept but are very labor intensive, often use remote locations, complex support equipment and are often constrained by weather conditions. This task in generally left to national organizations that have a vested interest in accurate, independent calibration and provide this service to solar cell vendors and customers. The primary use of calibrated solar cells is to provide a definitive performance standard to which all like solar cells can be compared. In the laboratory, a calibrated solar cell is placed in the solar simulator and the intensity adjusted so that the short circuit current (Isc) of the calibrated solar cell matches the Isc under AM0. Once the simulator intensity is set, cells with a similar spectral response can be measured.

Organizations interested in AM0 calibration have conducted a series of workshops since 1994 in order to create an international standard for calibrating solar cells. From these workshops three ISO standard documents are being developed. They are: ISO/TC 20/SC 14 N 165, ISO/DIS 15387, "Single-junction space solar cells -Measurement and calibration procedures", ISO/TC 20/SC 14 N213, ISO/WD23038, "Space solar cells-Electron and proton irradiation test methods" and ISO/TC 21/SC 14N 224, ISO/WD23039, "Space multi-junction solar cells- Calibration procedures". The calibration of single junction solar cells covered in ISO/DIS15387, describes 7 methods of calibrating solar cells. The methods are divided into two categories: So called "extraterrestrial" methods that include high altitude balloons and aircraft, where the solar cell is exposed to near AM0 conditions and "synthetic" methods, which use surface sunlight or laboratory solar simulators to illuminate cells. Each of these methods must make some corrections to the data to account for variations from the AM0 reporting condition of 1 astronomical unit from the Sun at 25°C.

In an effort to understand the various methods and compare results on identical cells, a calibration round robin was established between five different laboratories using four different techniques. They are; high altitude balloon flights conducted by the NASA Jet Propulsion Lab (JPL) and Centre National d'Etudes Spatiales (CNES), high altitude aircraft flights conducted by the NASA Glenn Research Center (GRC), the global solar method conducted by SPASOLAB for the European Space Agency (ESA), and the solar simulator method performed by the National Space Development Agency (NASDA).

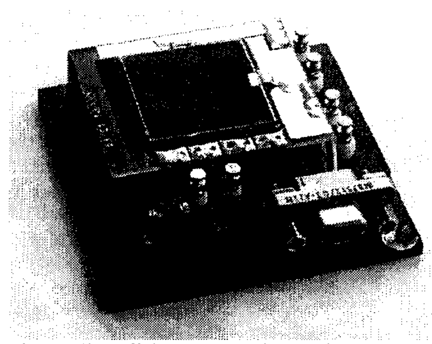

Figure 1) Cell holder developed for the round robin.

Six 2-cm x 2-cm cells, 3 GaAs single junction and 3 single junction silicon cells (one cell irradiated to $1 x 10^{15}$ 1 MeV electrons) were prepared for the round robin. A cell holder was designed that is compatible with all measurement methods. Each cell was mounted to a holder with three temperature sensors: a copper-constantan thermocouple (type T), a 100 Ohm RTD, and a temperature transducer made by Analog Devices model AD590. A photograph of a cell holder is shown in figure 1. It was up to the individual labs to use the temperature sensors as they applied to each calibration method. The reported results were short circuit current (Isc) at 25°C

and AM0 as defined by ISO/DIS15387, a total power density of 136.7mW/cm^2.
QinetiQ in the UK, has collected all of these data and serves as an independent entity to broker the data.

CALIBRATION METHODS

JPL high altitude balloon

The basic principle of calibration is to measure the short-circuit current of each flight cell since Isc 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 Isc. 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 20 ppm/°C. There is also the capability to measure full I-V curves by switching in 20 different resistor loads across the cell. The cells connected for full current-voltage curve measurement do not have fixed load resistors. The cells are exposed to direct extraterrestrial sunlight while they are carried on the high altitude (36.6 km) 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 aand/or shadowing from the balloon or from any part of the structure hanging below the balloon. Figure 2 shows the balloon schematically. 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

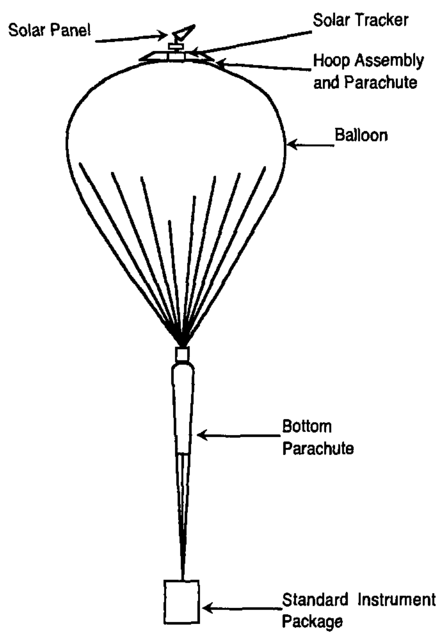

Figure 2) Configuration of the JPL balloon.

is for the Earth-Sun distance at the time of the flight, and the other is a temperature correction to a standard temperature.

CNES high altitude balloon

CNES calibrations are performed on-board stratospheric balloons flying at high altitudes (36 km) where the solar spectral irradiance is very close to AM0. The cells calibrated in this way can subsequently be used as standard solar cells 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.

An electronics payload is carried on-board the balloon's gondola, allowing the characteristic current-voltage relationship I = f(V) to be recorded as a function of temperature, under real AM0 illumination, with corrections made for the following: Residual atmosphere at the balloon's altitude. Variation of illumination caused by the varying Earth-Sun distance over the year. A sketch of the system is shown in figure 3.

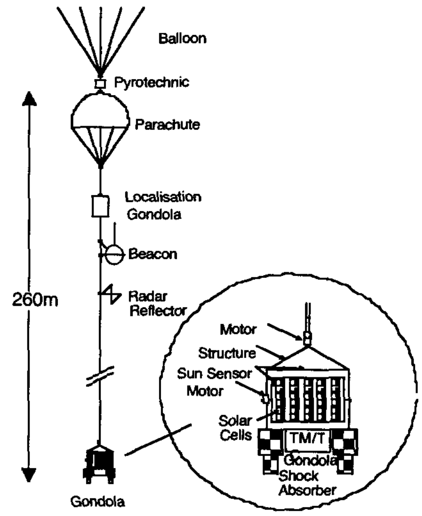

Figure 3) Configuration of the CNES balloon.

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 Voc (open circuit voltage) to 0 while Ic (cell current) increases from 0 to Isc. Ic and Vc (cell voltage) are measured after each programmed supply voltage. Up to 92 values of Ic and Vc can be measured for each curve.

High altitude aircraft calibration method

The short-circuit current (Isc) is obtained by exposing the solar cells directly to the Sun at high altitude. Data are obtained over a span of altitude, and a Langley-type plot is used to obtain the calibration value. Isc is plotted versus air mass (AM) and Isc at AM0 is obtained. Air mass M is defined in terms of the ambient pressure P (in atmospheres) and the solar elevation angle Hc as

$$M = P \sec(90 - H_c)$$

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.

Cells are mounted to a temperature controlled plate held at 25°C ±1°C with a 5:1 collimating tube attached. The tube is mounted inside of a Lear 25 aircraft (figure 4). Cells are actively biased to short circuit and the current measured using a calibrated source meter. Full I-V curves can also be taken in this manor by changing the bias voltage on the cell. Pressure and current measurements are taken as the aircraft descends from an altitude of approximately 15.4km to 10.8km at solar noon with the aircraft oriented so that the cells are perpendicular to the Sun.

Data is corrected to standard reporting conditions for Earth-Sun distance at the time flight and a correction for the residual atmosphere above 15.4km.[1]

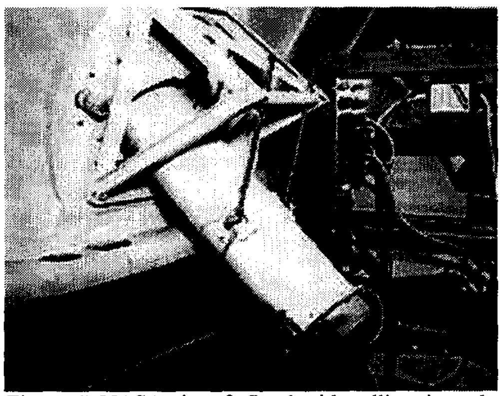

Figure 4) NASA aircraft fitted with collimating tube.

Global Calibration Method

In the global method, the cell (uncollimated), a spectroradiometer and a pyranometer are placed on a horizontal surface, and simultaneous readings of irradiance and short-circuit current are taken in global sunlight. The facility is located in one of the Canary islands (Tenerife) and operated by SPASOLAB. A photograph of the location is shown in Figure 5.

The global method involves the following steps:

(1) Measure the relative spectral response of the cell to be calibrated

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

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

(4) Measure the global, irradiance at the same time as the short-circuit current.

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

(6) Compute the calibration value.

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

Details of the calibration computation can be found in ISO/TC 20/SC 14 N 165, ISO/DIS 15387. An uncertainty analysis of the method is published in reference 2.

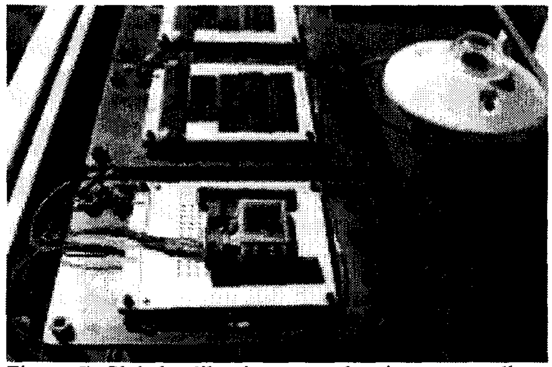

Figure 5) Global calibration stage showing a test cell and the pyranometer.

Solar Simulator Calibration Method

The solar simulator calibration method of an AM0 standard solar cell 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). This method is used by NASDA. A photograph of the simulator is shown in figure 6.

The solar simulator method uses these steps:

(1) The relative spectral response of the cell is measured at least three times with a white bias light of approximately 1367 Wm^{-2} (adjusted by a previously calibrated cell or a suitable detector) at a temperature of 25±1 °C. Data without a white bias light may be used if the cell does not have the bias light effect. The data [Q_l] is stored in a computer.

(2) The irradiance in the test plane of the solar simulator is set at approximately 1367 Wm^{-2}, by a previously calibrated cell or a suitable detector.

(3) 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).

(4) The cell is positioned in the test plane of the solar simulator. While the cell temperature is maintained at 25±1°C, the short-circuit current of the cell is measured before and after a measurement of spectral irradiance described in procedure (3).

(5) The calibrated I_{sc} for the solar cell is computed from the data by procedures (1), (3) and (4).
(6) Procedures (2) to (5) are repeated at least three times.
(7) The mean value of $I_{sc\ cal}$ is fixed as the definitive calibration value.

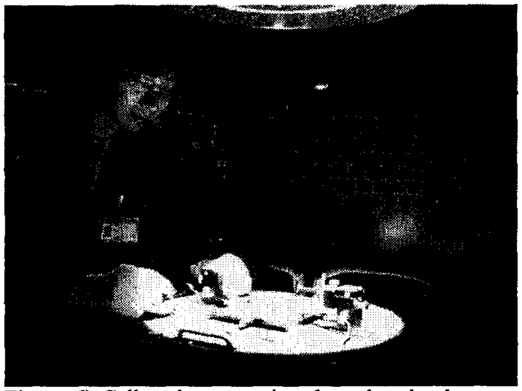

Figure 6) Cell under test using the solar simulator method of calibration.

ESTIMATING UNCERTAINTY

During the development of the ISO/TC 20/SC 14 N 165, ISO/DIS 15387 document, it was incumbent upon each laboratory to estimate the total uncertainty of their Isc calibration value. Table 1 lists the U_{95} (approximately 2 standard deviations) confidence level for short circuit current for each of the five methods.

Method/Lab	Total Estimated Uncertainty (U_{95})
Balloon/JPL	±0.5%
Balloon/CNES	±0.5-0.7%
Aircraft/NASA[3]	±2%
Global Sunlight/ SPASOLAB[2]	±1.3%
Solar Simulator method/NASDA[4]	±3.63%

Table 1) Estimated total uncertainty for each of the calibration methods.[5]

MEASUREMENT RESULTS

The round robin began with six cells; three GaAs (on GaAs substrates) and three single crystal silicon cells. One silicon cell was irradiated with 1MeV electrons to a fluence of $1x10^{15}/cm^2$. Not all cells were measured by all laboratories due to logistical and time constraints. NASDA supplied two different calibration values based on measurements traced to either a NIST standard lamp or an ETL standard lamp. However there are sufficient results to show a clear trend in the data. In spite of the wide variation in methods used to obtain the calibration values, the results are in very good agreement with each other. These results stand in marked contrast to the results of a previous measurement round robin, where silicon and GaAs cells were circulated and measured by laboratories using existing reference cells.[6] It was partly due to the disparity in the measurement round robin results, that the calibration round robin was organized. Clearly, the results show that the calibration of single junctions cell can be adequately address by a number of different methods. Transferring the calibration to other cells appears more difficult. This problem becomes even more challenging when multi-junction cells are measured. The participants in the round robin working gro[illegible]itional round robin activities to include calibration of multi-junction cells and measurement of multi-junction cells.

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[1] David B. Snyder, David A. Scheiman, Phillip P. Jenkins, William J. Rieke, and Kurt S. Blankenship, "Ozone correction for AM0 calibrated solar cells for the aircraft method," Proceedings of the 29th IEEE PVSC, May 19 to 24, 2002; Anaheim, CA, pp. 832-835.
[2] L.Garcia-Cervantes, J.M. Aguilar, A.Gras, M. Hernandez, E. Fernandez "Uncertainty Analisys for Ground sunlight calibration of space solar cells at Tenerife" Proceedings of the 17th Photovoltaic Solar Energy Conference, 22-26 October, Munich, Germany pp. 2259-2262.
[3] Phillip Jenkins, David Brinker and David Scheiman, "Uncertainty Analysis of High Altitude Aircraft Air Mass Zero Solar Cell Calibration", Proceedings of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA, Sept. 29 -O ct. 3, 1997.
[4] Minutes of the 8th international workshop on Space Solar Cell Calibration and Measurement Techniques, Freiburg, Germany, 17-19 October, 2001.
[5] Source is the ISO/DIS 15387 document for methods, not reference.
[6] S. Matsuda, D. Flood, T. Gomez, Yang Yiqiang, "Results from the first international round robin calibration and measurement of space solar cells," Proceedings of the 26th IEEE PVSC, Sept. 30 to Oct. 3, 1997; Anaheim, CA, pp. 1043-1047.

Holder No.	Cell Type	NASA	NASDA ETI	NASDA NIST	Spasolab	JPL	CNES
1	GaAs	100.9	99.5	97.91	-	101.7	-
2	GaAs	100.0	99.5	98.2	101.9	-	-
3	Si	100.6	100.8	99.6	98.6	100.2	100.3
4	GaAs	99.8	99.6	97.9	101.5	101.1	-
5	Si	99.6	100.8	99.4	100	100.1	100.1
6	Si (Irradiated)	100.3	100.3	99.1	100.7	99.6	-

Table 2) Comparison of solar cell calibration values normalized to the average value.

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[illegible]

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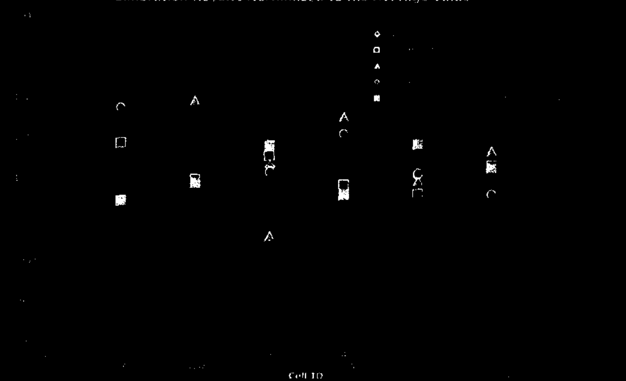
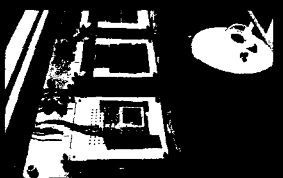
Calibration Results Compared to the Average Value

Holder No.	Cell Type	NASA	NASDA ETI std.	NASDA NIST std	Spasolab	JPL	CNES
1	GaAs	[illegible]	[illegible]	[illegible]		[illegible]	
2	GaAs	[illegible]	[illegible]	[illegible]	[illegible]		
3	Si	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	GaAs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
5	Si	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	Si (irradiated)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

Calibration Results Normalized to the Average Value





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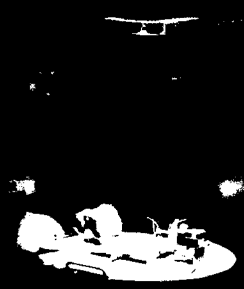

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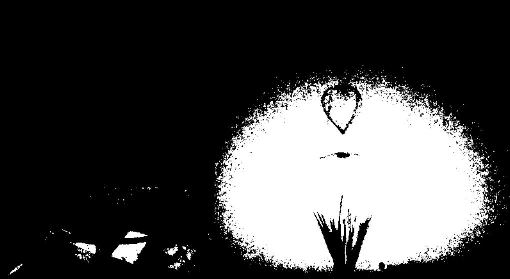
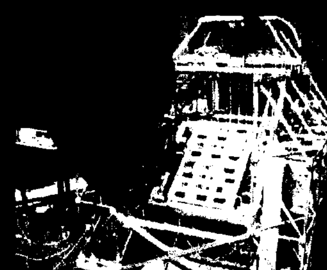
Aircraft Calibration

Cells are mounted to a temperature controlled plate held at 25°C ±1°C with a 5° collimating tube attached. Cells are actively biased to short circuit and the current measured using a calibrated source meter. Full I-V curves can also be taken in this manner by changing the bias voltage on the cell. Pressure and current measurements are taken as the aircraft descends from an altitude of approximately 15.4km to 10.5km at solar noon with the aircraft oriented so that the cells are perpendicular to the Sun. Data are obtained over a span of altitude, and a Langley type plot is used to obtain the calibration value. Isc is plotted versus air mass (AM) and Isc at AM0 is obtained. Data are corrected to standard reporting conditions for Earth Sun distance at the time of flight and a correction for the residual atmosphere above 15.4km.



JPL Balloon

The basic principle of calibration is to measure the short circuit current of each flight cell since Isc is directly proportional to the incident light intensity. The cells are exposed to direct extraterrestrial sunlight while they are carried on the high altitude (36.6 km) 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 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 a standard temperature.



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