PRIMARY SOLAR CELL STANDARDS – COMPARISON OF EXTRATERRESTRIAL AND SYNTHETIC CALIBRATION

C. Baur (1), G. Siefer (2), R. Kern (3), S. Winter (4)

(1) European Space Agency - ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands, Email: carsten.baur@esa.int
(2) Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, 79110 Freiburg, Germany,
(3) AZUR SPACE Solar Power GmbH, Theresienstr. 2, 74072 Heilbronn, Germany,
(4) Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany,

ABSTRACT

First results of a comparison between two sets of reference cells are presented of which one was calibrated using an “extraterrestrial” method in the frame of a CNES balloon flight while the other set was calibrated using the SI-traceable “synthetic” differential spectral responsivity method of the German metrological institute PTB. Measuring a representative set of 3G28 triple-junction solar cells from AZUR SPACE Solar Power GmbH against the two different sets of reference cells gave results which were in very good agreement with each other especially when taking into account the non-ideal conditions that had to be coped with during this study.

1. INTRODUCTION

The correct evaluation of the solar cell efficiency under the AM0 spectrum (also called calibration) is one of the key elements at the end of the production line of a solar cell manufacturer. The measured figures and its related uncertainties have an impact on both, the economical benefit for the solar cell manufacturer but also for the solar array manufacturer regarding the sizing of the solar generator.

The measurements of space solar cells are typically performed in a lab environment using dedicated solar simulators. As a reference, for the correct adjustment of the solar simulator spectrum, preferably so-called secondary working standards (SWSs) are used which match the cell to be measured in its spectral responsivity. These SWSs in turn are directly derived from primary calibrated reference solar cells (typically flown on a balloon or Lear Jet). Sets of primary reference cells (each comprising a top, middle, bottom single component cell and the respective triple-junction cell) are scarce since calibrations on the balloon or Lear Jet are quite expensive. Furthermore, opportunities for primary calibrations on balloon or Lear Jet are also quite rare, normally only once or twice a year.

On the other hand, the demand for primary reference cells will most probably increase in the following years. The next generation of solar cells will be based on rather new concepts probably also including new materials. Therefore, it can be expected that important development steps that justify a qualification which results in a new space solar cell product will occur more frequently in the upcoming years. However, each new production line requires its own primary reference cells. Additionally, it would be preferable not only to have one set of primary reference cells, but also reference cells for different irradiation levels. Furthermore, for quality assurance, calibrated reference cells should be recalibrated in regular intervals to insure that a possible degradation of these cells is detected and being corrected for.

Besides balloon or Lear Jet calibrations there are also other possibilities to generate primary standards which are less expensive and easily accessible. In the current issue of the ISO standard 15387 primary calibrations are typically classified in “extraterrestrial” calibrations and “synthetic” calibrations [1]. “Extraterrestrial” calibrations comprise principally only the balloon flight and Lear Jet calibrations. “Synthetic” calibrations are all other calibration techniques which are not using directly the “correct” AM0 spectrum but light sources which artificially aim for simulating AM0 conditions, like e.g. sun simulators or terrestrial sunlight.

It is currently under discussion that in the revised issue of the ISO standard only the “extraterrestrial” methods will be understood as “primary” calibrations. Nevertheless, “synthetic” methods would still remain in the standard as a valid option of generating reference standards. However, it is obvious that within the community synthetic standards will get fewer acceptances compared to extraterrestrial standards unless it is clearly demonstrated that both methods give comparable results within the respective confidence levels.

Making a first step towards a better acceptability of synthetic standards within the community, in this paper the results of a comparison of an SI-traceable (SI = International System of Units) synthetic method, namely the differential spectral responsivity measurement technique applied by PTB (Physikalisch-Technische Bundesanstalt – German national metrological institute) with an extraterrestrial method (CNES balloon flight) will be presented and discussed.

2. DESCRIPTION OF REFERENCE CELLS AND CALIBRATION METHODS

Two identical sets of solar cells have been used. In this context, "identical" has to be understood in that sense that the cells from both sets have been manufactured in the same MOVPE (metal organic vapour phase epitaxy) runs and also the encapsulation (application of coverglass, interconnectors and mounting on aluminium support plates) is done in an identical way. Each set comprises three component cells (top, middle and bottom) as well as one triple-junction (3J) solar cell. Thereby, component cells are single-junction solar cells being composed of almost the same layer structure as the corresponding 3J cell but with only one semiconductor material being electrically active. Thus, it can be assumed that component cells have identical optical and electrical properties as the corresponding sub cells in the 3J cell.
All solar cells relate to the 3G28 solar cell type from AZUR SPACE Solar Power GmbH (AZUR SPACE).

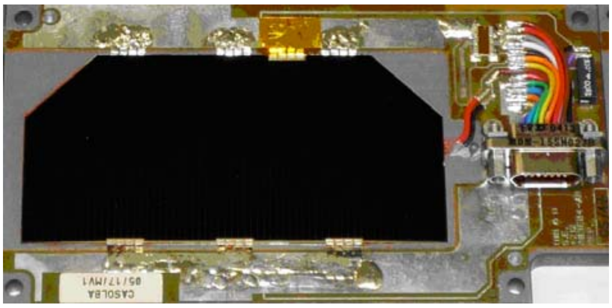

Figure 1. Picture of one reference cell attached to the CNES balloon flight module.

Fig. 1 shows an example of one of the reference cells attached to the CNES balloon flight holder. The cell has the typical 3G28 space solar cell shape – 4 cm x 8 cm with cropped corners – with a total area of 30.18 cm^2. The cell holder incorporates a 15-pin connector for measuring current, voltage and temperature. The temperature is measured using an AD590 temperature sensor integrated in the cell holder directly underneath the solar cell. Further information about the cell packaging can be found in [1].

2.1. "Extraterrestrial" primary reference cells

One of the sets (CNES set) has been calibrated within the CNES CASOLBA (CAlibration of SOlar cells using BAlloon flight) 2005 balloon flight activity. During such a flight a balloon with a gondola carrying the cells is brought into the stratosphere to an altitude of roughly 35 km. When the balloon has reached its maximum altitude the gondola with the cells is turned to face the sun for a few hours and the onboard electronics measures consecutively I-V curves of each cell by measuring the cell voltage V_C and the voltage V_R at the terminals of the load resistor R_C associated to each cell. The cell current I_C is given by $I_C = V_R/R_C$. For each I-V curve 92 points are measured between zero current (V_{OC}) and zero volts (I_{SC}). The I_{SC} is then determined by the voltage V_{RSC} which is measured at the terminals of the load resistor with the cell in short circuit.
Since there is no active cooling the whole setup slowly warms up during the flight - in the case of the 2005 flight activity from roughly -12 °C to +60 °C. In total 47 measurements have been performed for each cell within this temperature range (lowest temperature at begin, highest at the end of in-flight exposure).
The main purpose of this quite expensive and elaborate activity is to bring the cells as close as possible to AM0 conditions which correspond to the sun exposure outside the atmosphere. This is achieved by bringing the cells into the stratosphere where the remaining atmospheric absorption is very low. Then, the sun is used as an absolute irradiance source, thus no comparison with another absolutely calibrated solar cell or radiometer is done. Nevertheless, two main factors need to be taken into account in the data processing for obtaining highest accuracies: the residual atmospheric absorption at the balloon altitude and also the variation in earth/sun distance which depends on the date of the flight. In the 2005 CASOLBA flight activity the correction for the residual atmospheric absorption was less then 0.5 % for all cells whereas the correction for the earth/sun distance variation was roughly 3.5 %.
The calibration values at 25 °C (interpolated from the nearest in-flight data) for the extraterrestrial primary reference cells are given in Tab. 1. CNES claims an uncertainty of 0.5 % to 0.7 % for the calibration values.
A detailed description of the test procedure and the data processing together with the full description of the correction procedure is given in [1].

Table 1. Calibration data of the extraterrestrial primary reference solar cells

Cell flight reference	05-20MV1	05-21MV1	05-18MV1	05-19MV1
Cell type	Top	Middle	Bottom	3J
V_{RSC} [mV]	147.9	158.0	130.5	152.9
R_C [mΩ]	300.6	300.4	150.5	300.8
I_{SC} [mA]	492	526	867	508

2.2. "Synthetic" primary reference cells

The second set of reference cells (which is actually the spare set of the CASOLBA 2005 activity) has been calibrated at PTB in February/March 2011 (PTB set). The calibration method applied by PTB is called differential spectral responsivity (DSR) method. Although falling under the synthetic methods in the context of ISO 15387 [1] it is worth mentioning that this method is an absolute method according to IEC 60904-4 [2]. The basic principle of this method is to determine very accurately the absolute spectral responsivity of the test specimen (solar cell). The knowledge of the absolute spectral responsivity $SR(\lambda)$ allows then for calculating the photocurrent I_{photo} of the respective solar cell under any spectrum – thus also the AM0 spectrum $E_{AM0}(\lambda)$ - using the following equation:

$$I_{photo} = \int SR(\lambda) \cdot E_{AM0}(\lambda) \cdot d\lambda \qquad (1)$$

Here, $SR(\lambda)$ is the absolute spectral responsivity of the full size solar cell. This is actually the measure provided by PTB. The main features of the calibration procedure and the test setup which provide highest accuracies of the calibration results are the measurement of the spectral responsivity at several different bias intensities to account for possible non-linearities and the application of very homogeneous monochromatic light creating a spot which for all wavelengths is larger than the cell area. In addition, any small remaining inhomogeneities are corrected for. A detailed description of the calibration procedure and the test setup used at PTB are given in [3,4].
The calibration values of the set of solar cells that has been calibrated at PTB are given in Tab. 2. The AM0 spectrum used in the calculation of the calibration values using Eq. 1 is tabulated in [1] having a total irradiance level of 1367 W/m^2. PTB is claiming an uncertainty of 1 % on these calibration values where the tabulated AM0 spectrum is assumed to have no uncertainty.

Table 2. Calibration data of the synthetic primary reference solar cells.

Cell reference	05-16MV1	05-17MV1	05-22MV1
Cell type	Top	Middle	Bottom
I_{SC} [mA]	489	530	887

Together with the calibration values for a given spectrum PTB is also providing the absolute spectral responsivity data (see Fig. 2).
It has to be noted that the calibration method of solar cells at PTB is confined to single-junction solar cells. Thus, only the component cells have been calibrated at PTB which is also reflected in the presented results given in Tab. 2 and Fig. 2. However, this places no strong limitations to this calibration approach since for setting the solar simulator to AM0 conditions - which is actually the main purpose of these reference cells - typically only the component cells are used. If at all, the 3J cell is sometimes used for a final check of the solar simulator settings but most characterisation laboratories usually only use component cells. Thus, in the following comparison between both, the synthetic (PTB) and extraterrestrial (CNES) reference cell sets, the discussion will be focussed solely on the component cells.

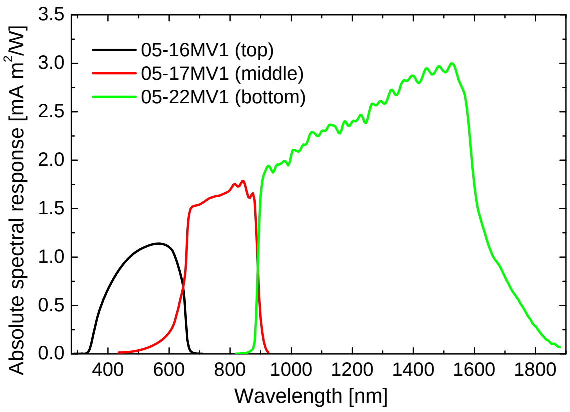

Figure 2. Absolute spectral responsivity data of the synthetic reference cell set calibrated at PTB.

3. STUDY APPROACH AND TEST RESULTS

The main objective of the presented study is to evaluate the differences or the consistency in the results one obtains when characterising 3J solar cells using either set of reference cells for setting up a solar simulator.
Therefore, a representative sample set of 8 AZUR SPACE 3G28 solar cells were selected out of the normal cell production. These cells were then measured against the CNES and also the PTB set of primary reference cells. Since all cells (3J cells and reference component cells) involved in this study are of the same cell type (3G28) with respect to layer structure, optical and electrical properties, any additional uncertainties that could originate from differences in spectral responsivities of reference cell and test cell was assumed to be rather small. Nevertheless, spectral responsivity was also measured on the 8 test cells to check and correct for spectral mismatches in the last step of the test sequence. The complete sequence of tests was as follows:

1. “Health check” of all reference cells (carried out at AZUR SPACE)
2. Calibration of the synthetic primary set at PTB.
3. Measuring the 8 3G28 3J cells by setting the simulator with the extraterrestrial set (no mismatch correction was applied)
4. Measuring the 8 3G28 3J cells by setting the simulator with the synthetic set (no mismatch correction was applied)
5. Measuring the 8 3G28 3J cells by setting the simulator with the synthetic set applying a mismatch correction using the spectral responsivities of the synthetic reference cell set provided by PTB and the spectral responsivity measurements performed on the 8 test samples carried out at Fraunhofer ISE.

All tests except for the first two were carried out at the Fraunhofer ISE using their three-source simulator as

described e.g. in [5]. Furthermore, all measurements performed in steps 2-5 were performed keeping the temperature of both, reference cell and test cell at 25°C.
The first step (health check) was actually carried out in order to verify that both, the primary reference cell set but especially the spare set (PTB set), shows no sign of any degradation. This was a prerequisite for the subsequent steps since only after the positive outcome of this test the spare set of the CASOLBA 2005 activity was sent to PTB for becoming the synthetic reference cell set.
In the framework of the health check at AZUR SPACE the spectral responsivities of top and middle component cells were measured (see Fig. 3) which shows that both, the two top cells and the two middle cells, match perfectly supporting the initial statement that the cells are quasi identical originating each from the same MOVPE runs. Thus, getting a first indication for how close or how different the results of the CNES and the PTB calibration are one can compare the calibration values of the two sets given in Tab. 1 and 2, respectively. Both, the calibration values of top and the middle cells which are the most important for the simulator adjustment are in good agreement (deviations below 1 %).

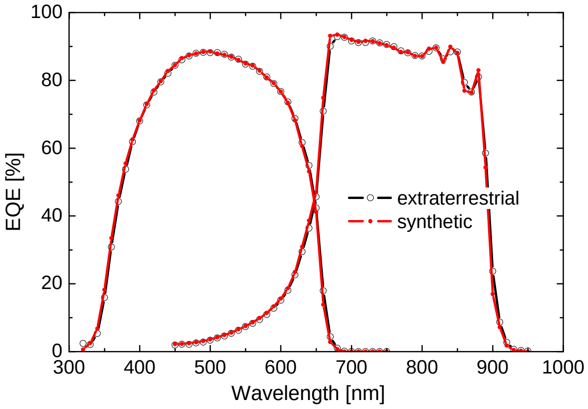

Figure 3. EQE of top and middle component cells of the extraterrestrial and the synthetic reference cell sets (measured by AZUR SPACE).

In Fig. 4 to 6 results are shown when measuring the 8 3G28 3J solar cells with the Fraunhofer ISE triple-source simulator using the two different reference cell sets for adjusting the simulator spectrum.
The procedure for setting the simulator was in both cases the same: In an iterative process the three light sources of the simulator were adjusted in a way that each component cell of the respective reference cell set was giving its calibration value.

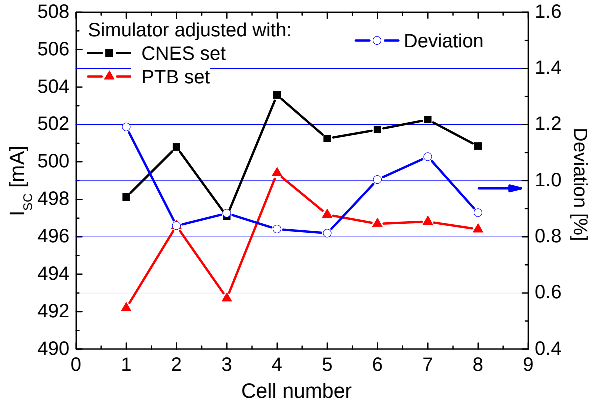

Figure 4. I_{SC} values of 8 AZUR SPACE 3G28 3J solar cells which were measured against the CNES and the PTB primary solar cell set. The deviations between the two measurements for each cell are given as well (open symbols).

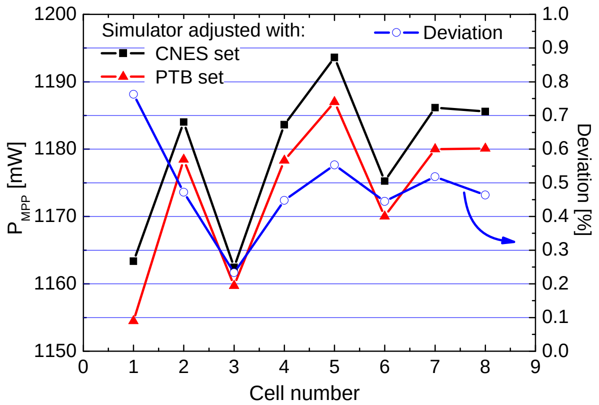

Figure 5. P_{MPP} values of 8 AZUR SPACE 3G28 3J solar cells which were measured against the CNES and the PTB primary solar cell set. The deviations between the two measurements for each cell are given as well (open symbols).

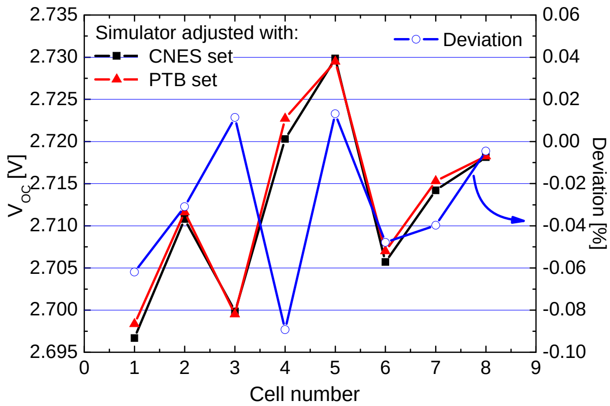

Figure 6. V_{OC} values of 8 AZUR SPACE 3G28 3J solar cells which were measured against the CNES and the PTB primary solar cell set. The deviations between the two measurements for each cell are given as well (open symbols).

When setting the simulator with the PTB reference cell set the measured I_{SC} values of the 3J cells are about 0.8-1.2 % below the corresponding values using the CNES set (see Fig. 4). However, for the maximum power point (P_{MPP}) the differences are clearly below 1% (except for one cell the differences are around 0.5%) as can be detected from Fig. 5. The V_{OC} values are actually only given for the sake of completeness. No major differences were expected there since the V_{OC} is insensitive to small spectral or intensity changes. As expected the deviations are below 0.1 % which demonstrates the excellent temperature control of the measurement setup and its reproducibility.
All in all, these results are very promising - all values are within the measurement uncertainties of the setup and – more important - the uncertainties given for the reference cells. However, we were actually expecting an even better match.
The top cell calibration values of the two sets (in Tab. 1 and 2) match quite well (0.6%). Thus, for the top cell limited 3J cells similar settings of the simulator were expected yielding to results which are in even better agreement as shown in figures 4 to 6.
Of course, the two top reference cells are not the same cells but nevertheless very similar (as shown in Fig. 3). So we were checking for reasons that could explain the slightly higher deviations in the measurements.
First of all, it has to be noted that both calibration sessions (the one with the CNES set and the one with the PTB set) were not carried out on the same day.
In addition just after the session with the CNES set has been accomplished a mirror in the xenon arc lamp housing of the 3-source simulator has been damaged and consequently replaced. In this context, one has to mention, that about 97 % of the top cell current is generated by the xenon lamp source. Thus, when a few weeks later the measurements with the PTB set have been performed the spectral distribution of the simulator has changed.

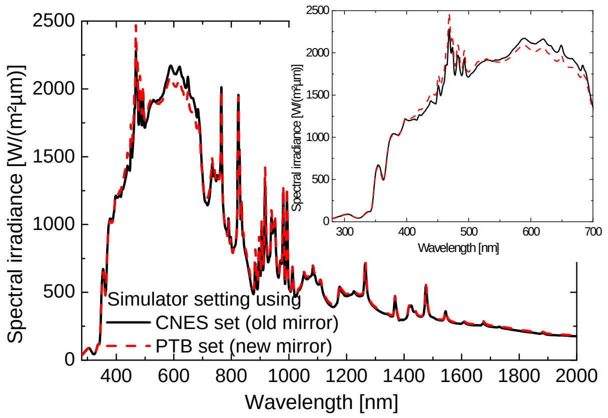

Figure 7. Simulator spectra under which the 8 3J cells have been measured when using the CNES (solid line) and the PTB set (dashed line), respectively.

Fig. 7 shows the final settings of the simulator after having adjusted the simulator with the CNES set and with the PTB set. From the inset in Fig. 7 it is obvious that the spectral distributions differ especially in the UV/visible part which can be attributed to the mirror which has been replaced inside the xenon lamp housing.
Since for all measurements the top cell is limiting the current of the 3J cell, it is obvious that any changes of the spectrum in the sensitivity range of the top cell can have a strong effect on the current of the 3J cell, especially for the case that reference and test cells do not show the same (relative) spectral responsivity. In Fig. 8 the differences in EQE between two representative top cells of the tested 3J cells and the reference cells are clearly visible. Spectral responsivities or EQE of all tested 3J cells have been measured at the Fraunhofer ISE, the EQE for the PTB reference cell shown in Fig. 8 is derived from the absolute spectral responsivity measurement given in Fig 2. The reason for the differences in EQE can mostly be ascribed to the coverglass that is applied to the reference cell.

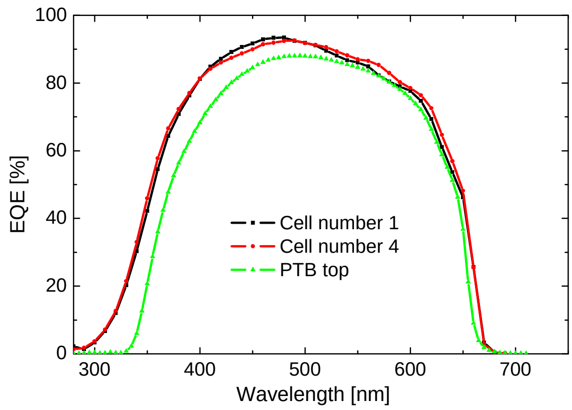

Figure 8. EQE of the top cells of 3J cell number 1 and 4 from the 3G28 3J sample set compared to the top component cell EQE from the PTB reference cell set.

Photocurrent densities for all top cells of the measured 3J cells were calculated according to Eq. 1 for both spectra shown in Fig. 8 and the AM0 spectrum using the respective spectral responsivities of the top cells. Although the absolute differences were quite small, the photocurrents calculated for the “CNES” spectrum for all cells gave higher values compared to the ones calculated for the “PTB” spectrum. Furthermore, the current densities calculated for the “CNES” spectrum were closer to those calculated for the “AM0” spectrum. This is an indication that the differences in the spectrum have led to the differences in the measurement.
Thus, an additional measurement session was carried out using again the PTB reference cell set but this time performing a spectral mismatch correction. The spectral mismatch correction procedure applied at the Fraunhofer ISE is based on solving the following linear equation system [5]:

$$\text{for } j \in \{top, middle, bottom\}:$$

$$\sum_{k=1}^{3} a_k \int s_j(\lambda) \cdot e_k(\lambda) \cdot d\lambda = \int s_j(\lambda) \cdot E_{AM0}(\lambda) \cdot d\lambda \quad (2)$$

Eq 2 yields three equations (one for each subcell of the 3J cell) for the three unknows a_k. The $e_k(\lambda)$ are the relative spectral distributions of the three light sources of the simulator and the $s_j(\lambda)$ are the relative spectral responsivities of the subcells of the 3J cell to be measured. To make the final adjustment of the simulator a reference cell set with known absolute spectral responsivity is required. Then each light source k of the simulator is set in a way that each reference cell j of the reference cell set gives a photocurrent according to:

$$I_{photo,j,k} = a_k \int SR_j(\lambda) \cdot e_k(\lambda) \cdot d\lambda \quad (3)$$

In our case, $SR_j(\lambda)$ is the absolute spectral responsivity of component cell j of the PTB set. Finally when all light sources are set according to Eq. 3 the photocurrent of each reference cell $j \in$ {top, middle, bottom} of the PTB set under the full solar simulator spectrum adds up to:

$$I_{photo,j} = \sum_{k=1}^{3} a_k \int SR_j(\lambda) \cdot e_k(\lambda) \cdot d\lambda \quad (4)$$

A more detailed description of the spectral mismatch correction procedure applied at the Fraunhofer ISE can be found in [5].

Performing the measurements with the simulator settings using the PTB reference cell set with spectral mismatch correction yields the results given in Fig. 9 and 10, respectively. I_{SC} values are now very close to the ones when using the CNES set.

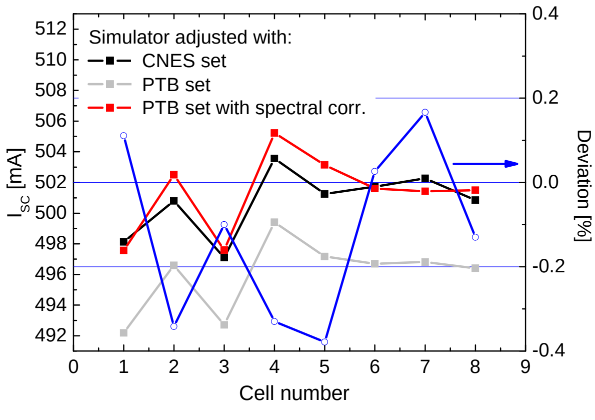

Figure 9. I_{SC} values of 8 AZUR SPACE 3G28 3J solar cells which were measured against the CNES set and the PTB set (with mismatch correction). For each cell the deviations between the measurements performed against the PTB set with mismatch correction and the CNES set are given as well (open symbols).

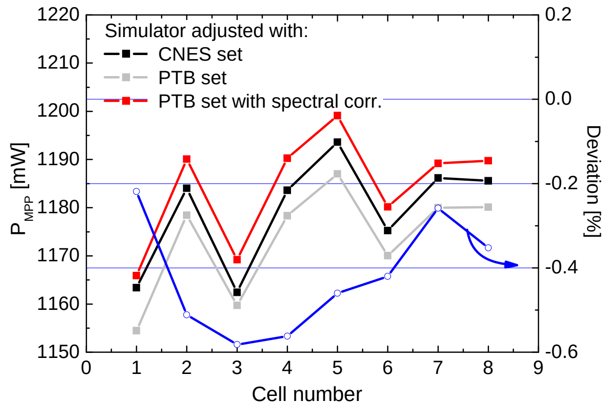

Figure 10. P_{MPP} values of 8 AZUR SPACE 3G28 3J solar cells which were measured against the CNES set and the PTB set (with mismatch correction). For each cell the deviations between the measurements performed against the PTB set with mismatch correction and the CNES set are given as well (open symbols).

Largest deviations are still below 0.4 % which is in the order of what can generally be achieved when repeating the same measurement at two different days. The same applies to the P_{MPP} values, where deviations are again as small as in the case without mismatch correction (< 0.6 %).

4. CONCLUSION AND OUTLOOK

Measurement results of 8 representative 3G28 3J cells from the daily production at AZUR SPACE have been presented using two different reference cell sets for setting up the three-source simulator at the Fraunhofer ISE. While both reference cell sets are quasi identical the sets were calibrated using two different methods: the “extraterrestrial” CNES balloon flight method and the SI traceable “synthetic” DSR method of PTB. Unfortunately, the measurements of the 3J cells against the two different sets of reference cells had to be carried out at different days - due to the high corporate value of the CNES reference cell set, this set was brought by an AZUR SPACE representative to the Fraunhofer ISE only for one day to perform the measurements. However, more relevant for the comparison of the results obtained with the two different sets was the fact that the two measurement sessions had to be carried out under different spectral conditions with respect to the optical characteristics of the spectral distribution in the UV/visible wavelength regime which has a significant impact on the top cell limited 3J cells.

Nevertheless, the measurements using the two different reference cell sets gave very consistent results with deviations in current of less than 1.2 % and in power of less than 0.8 %. Even smaller deviations could be achieved, when applying a spectral mismatch correction to the measurements performed with the PTB set. Then the deviations in current were less than 0.4 % and less than 0.6 % in power which are excellent results. Since it was also shown that test cells and reference cells do not necessarily have the same spectral responsivities, uncertainties can be higher when no mismatch correction is performed. This is of course very much dependent on the simulator spectrum.

Summarizing, the first step in demonstrating that the synthetic PTB calibration method is equivalent to the extraterrestrial CNES method has been successfully achieved. Additional measurements are planned where both sets will be at the same time at the same place (which was unfortunately not possible so far) using the same simulator with identical optical properties to validate the findings presented in this paper.

It shall be highlighted that it was not the intention of this paper to decide upon the question which of the two methods give the “better” (more accurate) results.

Assuming that principally the reference cell set using an “extraterrestrial” method is closer to the “truth” the intention was to show that an SI traceable synthetic method like the PTB method could be applied as an alternative. If this is positively validated also in subsequent measurement activities using the two different reference sets, one would have another source for generating reference cells which is less expensive and easier accessible. Furthermore, in the specific case of the PTB method, the absolute spectral responsivity is provided for the reference cell set which allows for applying a very accurate spectral mismatch correction in case needed.

Synthetic calibration methods could be used in the future at least for generating spare reference cell sets, which in addition are more frequently recalibrated to account for any possible degradation. Furthermore, they could be used for generating full sets of component cells which have been irradiated to different doses.

5. ACKNOWLEDGMENTS

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