Traceable calibration of photovoltaic reference cells using natural sunlight

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Abstract. At the European Solar Test Installation (ESTI) photovoltaic (PV) reference cells are calibrated traceably to SI units via the World Radiometric Reference (WRR) using natural sunlight. The Direct Sunlight Method (DSM) is described in detail and the latest measurement results and an updated uncertainty budget are reported. These PV reference cells then provide a practical means for measuring the irradiance of natural or simulated sunlight during the calibration of other PV devices.

1. Introduction
The price of PV modules is directly determined by their electrical performance at standard test conditions (STC). Therefore the independent determination of the electrical performance of PV modules with high accuracy (i.e. small measurement uncertainty) is important to guarantee fair and transparent markets. The (inevitably) remaining uncertainty contributes to the financial risk of PV module production and installation.

The electrical performance of PV modules is normally measured under pulsed simulated sunlight. The most difficult parameter to control and measure is the irradiance of the light (which should be 1000 W/m² at STC), whereas other quantities such as current and voltage are more readily available. PV reference cells are commonly used for the measurement of the irradiance of the simulated sunlight, as these have similar characteristics (in particular in response time) to the PV modules. The challenge is to calibrate these devices as irradiance sensors traceably with the lowest possible uncertainty. At ESTI this is achieved by calibration under natural sunlight against cavity radiometers, which are secondary standards for solar irradiance [1], directly traceable to the World Standard Group (WSG), which is the international primary standard for solar irradiance. Therefore traceability is to the World Radiometric Reference (WRR) and thereby SI units. This paper presents the DSM as implemented at ESTI and results obtained therewith.

2. Methods
The calibration of PV reference cells against natural sunlight can either use only the direct normal solar irradiance or alternatively the global in plane solar irradiance. In the former (DSM) only the direct sunlight (including the circumsolar) is used by excluding the other components (diffuse irradiance from the sky as well as reflected from the ground). This is achieved by suitable collimation tubes. The Global Sunlight Method (GSM) does not use such collimation tubes and therefore all
components of the irradiance contribute to the measurement. All methods are described in general terms in IEC 60904-4 [1]. The calibration has to be reported at STC which prescribes an irradiance of 1000 W/m² with a global spectral irradiance distribution according to IEC 60904-3 [2] and a device junction temperature of 25°C. Measurements are taken at conditions close to STC and appropriately corrected as described below.

2.1. Direct Sunlight Method (DSM)
The DSM has been used traditionally by NREL [3], and subsequently was first implemented at ESTI in 2005 [4]. In the meanwhile the set-up and method has been further refined and is described in detail here. In brief the direct solar irradiance is measured, the total with cavity radiometers and its spectral distribution with a suitable spectroradiometer. Furthermore the short circuit current of the reference cells is measured in parallel with the above mentioned parameters, while the cells are temperature controlled. The field-of-view of both the spectroradiometer and the reference cells is limited to the same angle as the cavity radiometers by suitable collimation tubes.

2.1.1. Instrumentation and mounting. The direct irradiance was measured with three cavity radiometers (PMO6 nr. 81109 and PMO6 nr. 911204 and TMI IV nr. 68835) directly traceable to the WRR via the International Pyrheliometer Intercomparison (IPC) [5]. The cavity radiometers have a field of view full angle of 5°. The spectral irradiance was measured with a spectroradiometer (OL 750) equipped with an integrating sphere and an additional collimation tube. The instrument was calibrated in-house against a standard lamp traceable to the SI irradiance scale via NPL. The PV reference cells were mounted on a water cooled mounting plate which allowed to maintain the reference cell temperature at (25±2)°C during measurements. Collimating tubes were mounted in front of the cells. All equipment was mounted on solar trackers automatically following the sun. All collimation tubes were designed to limit the field of view for the spectroradiometer and the reference cells to the same as it is for the cavity radiometers. Therefore all instruments are exposed to the direct solar irradiance only. The set-up is shown in figure 1 and figure 2.

Figure 1: The main set-up with the three cavity radiometers and reference solar cells below the collimation tubes. Further auxiliary instrumentation is also shown but not used for the DSM except for one of the pyrheliometers for monitoring the stability of solar irradiance.

Figure 2: The OL750 spectroradiometer with collimation tube attached to the integrating sphere.
2.1.2. Measurements. The two PMO6 instruments were operated on a 40 second cycle time, giving a data point every 80 seconds (40 seconds open and 40 seconds closed). The TMI instrument was read every 20 seconds. The short circuit current of the reference cells was recorded simultaneously with a multi-channel transimpedance amplifier and data logger together with the reading from the internal temperature sensor to the reference cells every 20 sec. The OL750 spectroradiometer was operated in automatic mode (using a suitable script) starting a new acquisition every 10 minutes approximately.

2.1.3. Irradiance correction. The following stability criteria were chosen: irradiance from the two PMO6 cavities within 1 W/m², irradiance stable to within ± 0.5% over 80 seconds (PMO6 cycle time), irradiance stable to within ± 1.0% over 300 seconds (OL750 cycle time). The irradiance stability is taken from the reading of a pyrheliometer (ser. Nr. 930018), which has a faster response time than the cavities (and is read every 20 sec). For data points fulfilling these criteria, the direct irradiance \( G_{dir} \) is taken as the average reading of all three cavities and finally accepted if larger than 750 W/m². A systematic shift between WRR and SI scale has been established [6]. Therefore the readings of the cavity radiometers were corrected to the SI irradiance scale by dividing the WRR reading by 1.0034. During stable conditions, an irradiance reading is therefore available every 80 seconds. The four short circuit current readings (20 sec) for each irradiance reading (80 sec) are averaged. The short circuit current scaled to 1000 W/m² \( (I_{SC}) \) is then calculated from the measured short circuit current \( I_{meas} \) by

\[
I_{SC} = I_{meas} \frac{1000 \text{ W}}{m^2} \frac{1}{G_{dir}}
\]

(1)

2.1.4. Temperature correction. Considering the narrow temperature range no correction for cell temperature was made. The deviation of up to \( 2^\circ \text{C} \) from the target temperature of \( 25^\circ \text{C} \) is treated as a measurement uncertainty component and explicitly included in the respective calculation.

2.1.5. Spectral correction. The direct spectral irradiance data from the OL750 were visually inspected and all spectra which showed signs of instability or artefacts were eliminated. The acquisition of a single spectrum takes 5 to 6 minutes, and is sequential in wavelength, starting at 300 nm up to 2500 nm. Instable conditions (e.g. moving clouds) lead to decreased or increased signal in some parts of the spectrum, thereby distorting its shape. They are easily identified by visual inspection comparing with the daily average and the reference spectrum [2]. A spectral correction was applied for each data point according to

\[
CV = I_{SC} \frac{\int SR_{DUT}(\lambda) E_{ref}(\lambda) d\lambda}{\int SR_{DUT}(\lambda) E_{meas}(\lambda) d\lambda} \frac{\int E_{meas}(\lambda) d\lambda}{\int E_{ref}(\lambda) d\lambda}
\]

(2)

with \( CV \) the calibration value at STC, \( I_{SC} \) from equation (1), \( E_{meas} \) the measured spectral irradiance, \( E_{ref} \) the reference global spectral irradiance [2], \( SR_{DUT} \) the spectral responsivity of the reference cell and \( \lambda \) the wavelength.

2.1.6. Integration range. The data were interpolated and then integrated from 300 nm to 2500 nm. This introduces a systematic error, as the integration in equation (2) should be over all wavelengths, i.e. from zero to infinity. The lower integration limit of 300 nm does not introduce any effect as the spectral irradiance below this wavelength can be neglected [2]. However, above 2500 nm there are 10.3 W/m² in both, the global and the direct reference spectra [2]. This affects only the two integrals in the second fraction in equation (2), as the SR of reference cells vanishes above 1200 nm. The irradiance missing from the two integrals is the same in absolute terms for global and direct spectra,
but has a different relative contribution as the total irradiances of the two spectra are 1000 W/m² and 900 W/m² respectively. Therefore a correction factor of 1.00116 was calculated (approximating the measured spectra with the direct reference spectrum) and applied.

2.1.7. Averaging. The data were averaged [1] as summarized below. For each acquired spectrum typically seven \( I_{SC} \) values were available, sometimes less due to the described filtering. All available values per spectrum were averaged, but if there were less than four data, the point was eliminated. Then all results from each day were averaged with a minimum of five data points per day. Finally the results of all days were averaged with a minimum of at least three days for a valid \( CV \) as required by IEC 60904-4 [1].

2.2. Global Sunlight Method (GSM)
The GSM has already been described extensively in the past [7].

3. Results
Here we report the results of the two most recent calibration campaigns in 2014 and 2015. In 2014 five ESTI PV reference cells (PX201C, PX301C, PX304C, 930417-2 and ASP010) were calibrated on 31 of July, 4 and 21 of August 2014. In 2015 two of the former (PX201C and PX301C) were re-calibrated on 20, 21 and 22 of April 2015. The other cells were also measured in 2015 but it was not possible to obtain data on three different days, and therefore no full calibration was achieved. All reference cells are crystalline silicon.

3.1. Spectral irradiance
Measured spectra of direct solar irradiance for 4.8.14 and 20.4.2015 are plotted in figure 3 and figure 4. A certain spectral variation during the day is observed due to the change of the path length of the solar direct beam within the atmosphere. All measured spectra deviate from but are similar to the reference spectrum. This was analysed by classifying all spectra according to IEC 60904-9 [8]. This showed that all spectra were meeting the requirements for class A and 95% of all spectra had deviations from the reference spectrum less than half the allowed limit specified for class A. The analysis in IEC 60904-9 [8] is limited to the wavelength range 400 nm to 1100 nm. However, this corresponds to where the spectral responsivity of the reference cells is significant. Therefore, it gives a good indication that for the reference cells investigated here the spectrum of natural sunlight is similar to the reference spectrum. The deviations from the latter are corrected for with equation (2).

![Figure 3: Measured direct solar spectral irradiance on 4.8.14 with reference spectrum (in red).](image)

![Figure 4: Measured direct solar spectral irradiance on 20.4.15 with reference spectrum (in red).](image)
3.2. Short circuit current and calibration values
As an example the data analysis for cell PX301C in 2015 is shown in figure 5. Table 1 lists all results from both campaigns, for single days as well as the final averaged CV. The spread of the data for cell PX201C in 2015 is somewhat larger due to limited (but still sufficient) number of data points.

3.3. Measurement uncertainty UC
The UC budget for DSM and GSM has been updated after the shift of the WRR to SI irradiance scale had been implemented. Previously the uncertainty of scale difference had been estimated to be 0.3% with rectangular distribution (i.e. 0.17% $k=1$). The recently established scale shift has a lower uncertainty of 0.09% ($k=1$). Thereby the overall combined expanded uncertainty of the DSM method is 0.48% ($k=2$) (table 2). The respective uncertainty for the CV of each of the reference cells is included in table 1.

![Figure 5: Data analysis for reference cell PX301C in 2015. The blue squares are the as measured short circuit current $I_{\text{meas}}$, the red dots the $I_{\text{sc}}$ (scaled to 1000 W/m$^2$) and the green triangles the results after spectral correction. The black horizontal lines are the daily averages calculated from the latter.](image)

Table 1: The results for all cells in 2014 and 2015 for the single days and the average. All values are in mA.

|            | ASP010 | PX201C | PX301C | PX304C | 930417-2 | PX201C | PX301C |
|------------|--------|--------|--------|--------|----------|--------|--------|
| 31.07.14   | 79.81  | 123.43 | 125.45 | 124.31 | 123.80   | 20.04.15| 123.90 | 125.85 |
| 04.08.14   | 79.87  | 123.65 | 125.67 | 124.57 | 123.94   | 21.04.15| 124.14 | 125.63 |
| 21.08.14   | 79.75  | 123.35 | 125.36 | 124.26 | 123.65   | 22.04.15| 122.95 | 125.17 |
| **Average**| **79.81** | **123.48** | **125.49** | **124.38** | **123.80** | **Average** | **123.67** | **125.55** |
| UC ($k=2$) | 0.34   | 0.59   | 0.60   | 0.60   | 0.59     | UC ($k=2$) | 0.59   | 0.60   |
Table 2: Uncertainty budget for DSM and GSM against SI units before (WRR) and after (SI) shift of the WRR irradiance scale. All contributions are listed as standard UCs in %.

| Uncertainty component          | DSM (WRR) | DSM (SI) | GSM (WRR) | GSM (SI) |
|--------------------------------|-----------|----------|-----------|----------|
| Data acquisition               | 0.06      | 0.06     | 0.06      | 0.06     |
| Temperature effects            | 0.06      | 0.06     | 0.06      | 0.06     |
| Irradiance                     | 0.11      | 0.11     | 0.24      | 0.24     |
| Spectral correction            | 0.18      | 0.18     | 0.18      | 0.18     |
| WRR offset to SI               | 0.17      | 0.09     | 0.17      | 0.09     |
| Combined standard UC (k=1)     | 0.29      | 0.24     | 0.35      | 0.32     |
| **Combined expanded UC (k=2)** | **0.58**  | **0.48** | **0.70**  | **0.64** |

4. Summary and conclusions
The DSM as implemented at ESTI provides calibration of PV reference cells under natural direct solar irradiance against secondary standards for solar irradiance and is traceable to SI units via the WRR. The expanded UC is below 0.5% (k=2). Here the results obtained in 2014 and 2015 for five different cells are reported. The cells are then used to measure the irradiance of natural and simulated sunlight during the calibration of electrical performance of other PV devices, providing the traceability for these measurements. Furthermore the results contribute to the determination of key comparison reference value (KCRV) for each reference cell, reducing further their uncertainty and establishing the World PV Scale (WPVS) [9].

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