# PRIMARY REFERENCE CELL CALIBRATION AT THE PTB BASED ON AN IMPROVED DSR FACILITY

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ABSTRACT: Based on several hardware and software improvements of the first DSR facility replacing also a number of components, both the typical operating times and the uncertainties have been reduced by a factor of two. The modifications of the DSR facility are described and the improvements are illustrated. An important aim was to improve the PTB's capability of carrying out the second WPVS recalibration in 2001 more efficiently.

Keywords: Calibration – 1: Spectral Response – 2 : WPVS World PV Scale – 3

## 1. INTRODUCTION

The PTB is one of the four qualified WPVS laboratories and the only European one that was included in establishing and presently maintaining the World Photovoltaic Scale (WPVS) used as a world-wide reference value for the calibration of primary reference solar cells and terrestrial PV performance measurements [1]. Such a global reference scale is the basic requirement for the mutual recognition of PV calibration certificates.

In the calibration of (terrestrial) solar cells and PV modules, the short-circuit currents $I_{\mathrm{STC}}$ and finally the conversion efficiencies both weighted according to the reference solar spectrum have to be determined under Standard Test Conditions (STC); i. e., $E_{\mathrm{STC}} = 1000\,\mathrm{Wm}^{-2}$ total irradiance, 25 °C cell temperature, AM1.5 reference solar spectral irradiance distribution $\partial E_{\mathrm{STC}}(l)/\partial l = E_{\mathrm{STC},l}$ of IEC 904-3, which is given in tabular form [2]. AM is the relative optical air mass. All the results in this paper are also valid if AM1.5 is replaced by, e. g., AM0.

The special difficulties of accurate solar cell calibrations are due to the high level of irradiance and large areas of the devices up to more than 100 cm² (cells) or 1 m² (modules) in connection with (i) the different spectral distributions of solar cell responsivities, (ii) the different and varying spectra of natural sun or solar simulator and the reference solar spectrum (double spectral mismatch) and (iii) the potential non-linearities of the short-circuit or photo-current at high irradiance levels [3].

Primary calibrations are carried out against radiometric standards (standard detectors and in addition standard lamps if necessary) traceable to SI units, while secondary calibrations against another reference cell are non-primary and non-independent and, therefore, correlated calibrations. The primary calibration methods applied by the four qualified WPVS laboratories are variously traceable to radiometric standards [1,3]. While the PTB uses a spectral method (see below), the other three laboratories (JQA/ETL in Japan, NREL in USA, TIPS in China) use integral methods with spectral mismatch correction based on the measurement of the relative spectral responsivity without determining the absolute spectral responsivity in Equation (1) directly.

$I_{\mathrm{STC}}$ is the required calibration value given by

$$I_{\mathrm{STC}} = s(l_0, E_{\mathrm{STC}}) \int\limits_{s(l)\neq 0} s(l, E_{\mathrm{STC}})_{\mathrm{rel}}\, E_{\mathrm{STC},l}\,(l)\,\mathrm{d}l \qquad (1)$$

Due to practical measuring conditions in radiometry (it is almost impossible to produce monochromatic radiation fields that are perfectly uniform at all wavelengths), relative spectral responsivity $s(l)_{\mathrm{rel}}$ covering the whole spectral range on the one hand and absolute spectral responsivity $s(l_0)$ of a solar cell (or detector) at discrete wavelength(s) $l_0$ on the other hand are measured separately. The variable $E_{\mathrm{STC}}$ indicates that the spectral responsivity of the (non-linear) cell has to be determined at the required high bias irradiance level $E_{\mathrm{b}}=E_{\mathrm{STC}}$ (i. e., not at low levels).

## 2. IMPROVED DSR FACILITY

The differential spectral responsivity (DSR) method is a spectral calibration method based on the measurement of the DSR as a function of wavelength $l$ in the presence of steady-state solar-like bias irradiance $E_{\mathrm{b}}$ setting the operating point which is determined by the short-circuit current $I_{\mathrm{sc}}(E_{\mathrm{b}})$:

$$\tilde{s}(l) = \left.\frac{\Delta I_{\mathrm{sc}}}{\Delta E(l)}\right|_{I_{\mathrm{sc}}(E_{\mathrm{b}})} \qquad (2)$$

with modulated quasi-monochromatic irradiance $\Delta E(l)$ and photo-generated ac short-circuit current $\Delta I_{\mathrm{sc}}$. $\tilde{s}$ is the slope of the short-circuit current / irradiance characteristic. The measurement of the spectral responsivity without bias radiation according to Equation (1) is only acceptable and correct if the solar cell to be calibrated is perfectly linear ($\tilde{s}\,(l,E_{\mathrm{b}}) = s(l)$ independent of $E_{\mathrm{b}} \leq E_{\mathrm{STC}}$).

In the PTB's DSR calibrations with varying bias radiation $E_{\mathrm{b}} \lesseqgtr E_{\mathrm{STC}}$ including a linearity test, both the relative and the absolute spectral DSRs of a reference solar cell under test are determined. A dual-beam optical arrangement is used to measure relative but equally normalized DSR spectra of a reference cell at a series of discrete operating points that are set with a steady-state bias radiation at levels between $0.001E_{\mathrm{STC}}$ and $2E_{\mathrm{STC}}$ (see Fig. 1). The chopped monochromatic radiation behind a double grating monochromator is measured with lock-in technique where the monitor photodiodes fixed within the spectroradiometer are calibrated against calibrated standard detectors (Si and InGaAs photodiodes) not exposed to the bias radiation (!) while substituting the test cell. To scale

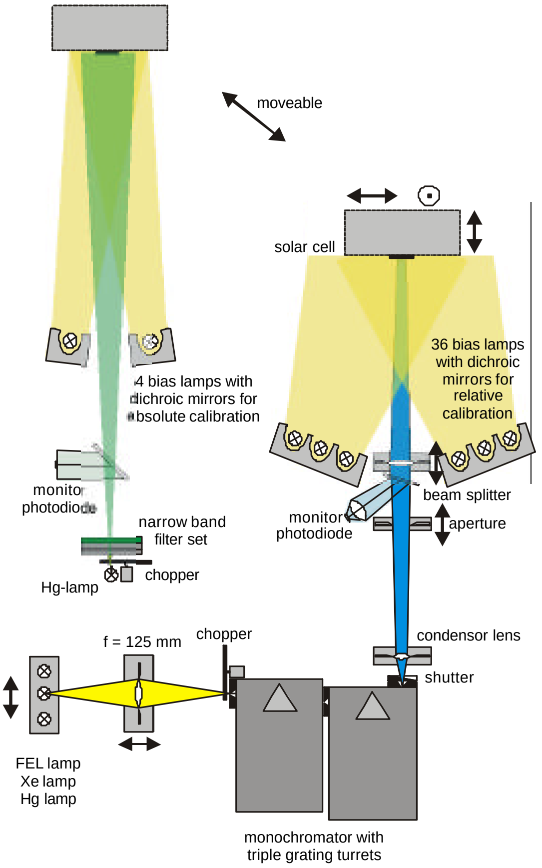

**Figure 1.** New version of the PTB's DSR Calibration Facility combining relative DSR spectroradiometer and absolute DSR filter monochromator. Monitor photodiodes are used to improve stability and reproducibility. The radiation shields are not included in this figure.

the relative DSR, the absolute DSR $\tilde{s}\,(l_0, E_0)$ at one (or more) appropriate discrete wavelength(s) is measured at one low (but well-defined) bias level $E_0$ (about 20 $\mathrm{W m^{-2}}$) using a filtered medium-pressure Hg lamp. In contrast to the first DSR facility operated since 1987, the optical arrangement for the absolute DSR calibration is integrated into the new DSR calibration facility producing uniform spectral irradiance all over the cell area of up to 200 $\mathrm{cm^2}$ without imaging optics. The modulation frequencies (about 135 Hz) for the relative and absolute DSR measurements are identical. More absolute calibrations at various wavelengths can be performed as a consistency check [4] (see also below). If a cell is linear and the (spectral) responsivity independent of (bias) irradiance, the calibrated responsivity is simply the mean of all the measured responsivities and Equation (1) is used to calculate $I_{\mathrm{STC}}$. For the case of a non-linear cell, a simple iterative integration procedure is used to obtain $I_{\mathrm{STC}}$ [5]:

In the general case of non-linear cells, Equation (1) is not used but the AM1.5-weighted differential responsivity is calculated from the DSR data

$$\tilde{s}_{\mathrm{AM1.5}}(E_{\mathrm{b}}) \cdot E_{\mathrm{STC}} = \tilde{s}(l_0, E_0) \cdot \int_{s(l)\neq 0} \tilde{s}(l, E_{\mathrm{b}})_{\mathrm{rel}} \cdot E_{\mathrm{STC}}(l)\,\mathrm{d}l \qquad (3)$$

The calibration value $I_{\mathrm{STC}}$ of non-linear cells is obtained with the aid of a simple integration over the short-circuit current $I_{\mathrm{sc}}(E_{\mathrm{b}})$ by approximating the unknown upper integration limit $I_{\mathrm{STC}}$ within a few steps (see in Fig. 2 the non-reciprocal weighted differential responsivity versus short-circuit current)

$$E_{\mathrm{STC}} = \int_0^{I_{\mathrm{STC}}} \tilde{s}^{-1}_{\mathrm{AM1.5}}(I_{\mathrm{sc}})\mathrm{d}I_{\mathrm{sc}} \qquad (4)$$

with $s_{\mathrm{STC}} = s_{\mathrm{AM1.5}}(E_{\mathrm{STC}}) = I_{\mathrm{STC}} \cdot E^{-1}_{\mathrm{STC}}$.

Applying the efficient DSR method applicable to all kinds of reference solar cells independent of technology, the unit of spectral responsivity is transferred to high levels of irradiance including a linearity test covering the spectral range from 250 nm to 1600 nm without any gap. The standard detectors used are traceable to SI units via laser and broadband cryogenic radiometers. Fig. 3 shows the calibration chains in the PTB relating the calibration of solar cells and PV modules to national radiometric standards. Grey symbols indicate the direct calibration chain, while white symbols are used for the additional chain needed to determine spectral irradiance data for spectral mismatch corrections. The chains to the standard detectors and lamps are identical to the PTB's basic radiometric chain for the realization of the radiometric and photometric units. The main traceability chain from primary to secondary reference cells and to reference modules requires calibrations under natural or simulated solar radiation using steady-state or pulsed simulators. Spectral mismatch correction is in general required to reduce the relative calibration uncertainty to < 5 %. Spectroradiometers and filter sets [6] in combination with standard lamps are therefore used to correct the spectral mismatch between the PV devices on the one hand and the reference and solar/simulator spectra on the other hand.

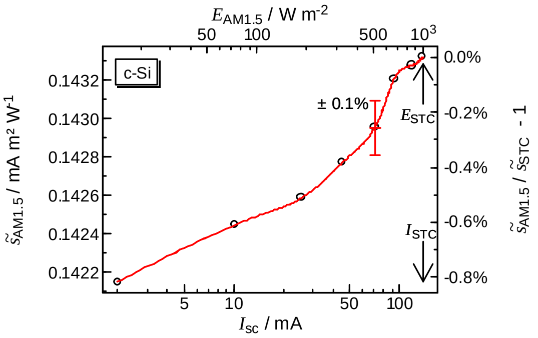

**Figure 2.** Weighted differential responsivity of a mono-crystalline Si solar cell as a function of short-circuit current.

## 3. PERFORMANCE

Applying the DSR method for the calibration of primary reference cells at the PTB's first DSR facility since 1987 until quite recently, expanded uncertainties (k=2) of 1% (95% level of confidence) were obtained [3,4]. However, the DSR calibration is a rather time-consuming and thus costly business. Although 1% uncertainties of primary reference cells are reasonable, a markedly reduced uncertainty is desirable allowing a corresponding reduction of the uncertainty of secondary reference cells (see the calibration chain in Fig. 2). Therefore, the modifications of the improved DSR facility aimed at the reduction of both the operating time and the uncertainty focusing first on the improvement of the calibration of WPVS cells. The improvements are based on recent progress in radiometry and on the experience of operating the first DSR facility for more than 12 years.

The most important improvements of the new DSR facility are summarized as follows (see Fig. 1): extension of the spectral range (250 nm to 1600 nm) by using a double monochromator with triple grating turrets covering the whole wavelength range without any gap using programme-controlled selection of the gratings; integration of the setup for the absolute calibration at discrete wavelength(s) into the relative calibration; lens optics instead of mirror optics to avoid spherical abberation whereas the chromatic errors of the lenses are compensated by automatic moving the lenses as a function of wavelength; one double monochromator with triple grating turrets in subtractive dispersion instead of two monochromators with single grating turrets in order to (i) cover the whole spectral range and (ii) improve uniformity within the optical beam (up to 120 x 120 mm$^2$); monochromatic light source (Hg lines produced by a medium-pressure Hg lamp with narrow-band filter set) for the absolute calibrations; mapping option for spatially resolved spectral response measurements (see below); improved automation and on-line data evaluation.

As a first result, both measurement time (operating time when the programme-controlled DSR facility is busy) and labour (actual input of staff and thus calibration fee charged) were reduced to about half the previous times. This improvement is mainly based on (1) the programme-controlled integration of the absolute DSR calibration procedure without extra alignment and without a second temperature control of the cell, (2) the use of only one monochromator resulting in alignment simplification, (3) improved automation and on-line data evaluation.

The reduction of the measurement uncertainty to again half the previous value (see Table I) is mainly based on (1) the reduction of the uncertainty of the Si and InGaAs photodiodes used as standard detectors which can directly be calibrated against the broadband cryogenic radiometer according to the new radiometric calibration chain illustrated in Fig. 2, (2) the reduction of the spectral bandwidth of the monochromatic radiation for relative (≤ 18nm to ≤ 11nm of the monochromators) and absolute DSR measurements (10nm of the filter monochromator to < 1nm of Hg lines), (3) better temporal stability and spatial uniformity ($\delta l < 0.4$ nm over cell area) of the well-defined centre wavelength of the monochromatic radiation, (4) doubled spectral irradiance and improved uniformity of the monochromatic radiation, especially for the calibration of WPVS cells, (5) improved image of the aperture on the solar cell behind the monochromator due to reduced image defects (spherical aberration), (6) improved electronics and signal-to-noise ratio, especially due to digital lock-in amplifiers, (7) improved temperature control.

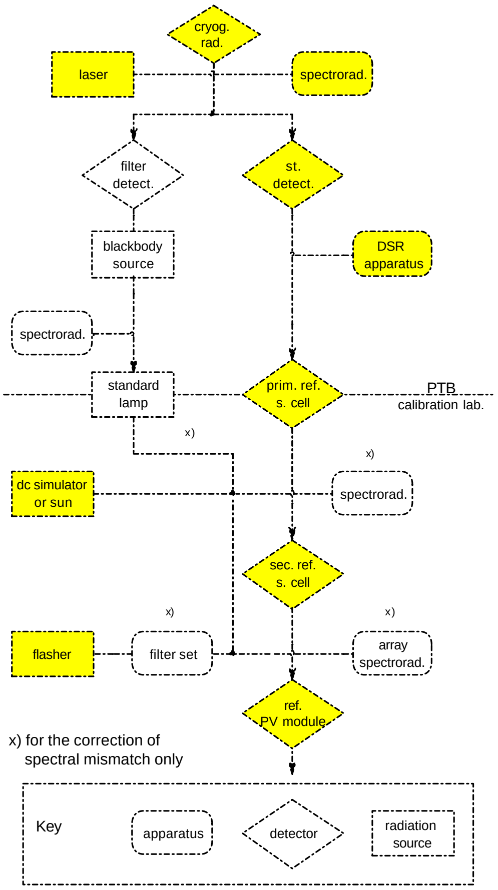

**Figure 3.** PTB's traceability chain for the calibration of PV devices.

**Table I.** PTB's DSR calibration: Uncertainty budget optimized for the calibration of WPVS cells.

| | |
|---|---|
| **Type A uncertainty:**<br>Uncertainty due to unstable cell temperature (± 0.5 K) | < 0.05 % |
| **Type B uncertainties:**<br>Uncertainty of the standard detector(s) | < 0.1 % |
| Uncertainty due to nonlinear and/or narrow-band cells | < 0.05 % |
| Transfer uncertainties (repeatability) due to<br>relative spectral responsivity<br>absolute spectral responsivity at discrete wavelength(s)<br>spectral mismatch between bias radiation and reference solar spectrum; non-uniformity of bias radiation; non-uniformity of monochromatic radiation; mismatch of cell area and irradiated area (image of the aperture); spectral bandwidth (≤ 11 nm) of the monochromatic radiation; nonlinearity of the amplifiers | <br>0.05%<br>0.05%<br>0.2 % |
| Combined standard uncertainty | 0.25 % |

It was not necessary to improve the spectral match and the uniformity of the bias irradiance [7] and of the simulated solar radiation for the determination of fill factor and open-circuit voltage [4]. Moreover, it has been checked by varying the image $A^*$ of the aperture on the cell (cell area A) within a wide range $0.25A \leq A^* \leq 0.98A$ that the uncertainty due to the mismatch $A^* \neq A$ is $< 0.05\%$ in practice if $A^*$ is always less than A (see also [7]). Strictly speaking, the relative DSR measurement is a calibration with respect to spectral radiation power (using a optical beam smaller than the active area of the device), while the absolute DSR measurement is a calibration with respect to spectral irradiance (using a large uniform radiation field).

In addition, it has been proven that absolute DSR measurements can be carried out at every wavelength behind the monochromator (see Fig. 1) by using a mapping procedure: the solar cell is moved two-dimensionally resulting in a scan of the monochromatic optical beam of almost any diameter. Thus, flexibility of the DSR facility and the possibility of characterizing solar cells is increased.

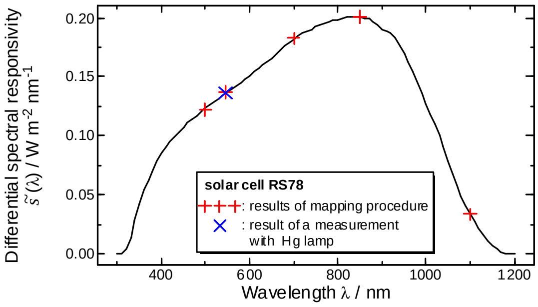

Figure 4. Scaling of the relative DSR by absolute DSR measurements (see text).

Fig. 4 shows the results of the absolute DSR calibration at the 546.1 nm Hg line compared with five mapping measurements that can be carried at any one wavelength to obtain also absolute DSR calibrations. The standard deviation of the five absolute DSR data (based on the mapping procedure) to the absolute DSR (relative DSR combined with absolute DSR at one Hg line) was found to be 0.15%. Moreover it has been shown, that the data of the mapping measurements are independent of the diameter of the scanning optical beam within wide limits.

## 4. CONCLUSION

Based on several hardware and software improvements of the first DSR facility and replacing a number of components, both the typical operating times and the uncertainties have been reduced to half their previous values. Expanded uncertainties of 0.5% (95% level of confidence) are obtained now. Thus, the new DSR facility is well-equipped for the second WPVS recalibration campaign to be carried out at the PTB in 2001 (see also [1,8]).

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