COMPREHENSIVE ANALYSIS OF A PULSED SOLAR SIMULATOR TO DETERMINE MEASUREMENT UNCERTAINTY COMPONENTS

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ABSTRACT: For solar cell efficiency measurements the accurate determination of the short circuit current under standard test conditions (I_{STC}) is vital. This contribution is focused on the applicability of flashers for a traceable calibration of the short circuit current of large area crystalline silicon solar cells. In order to obtain measuring results traceable to SI-unit system, an uncertainty analysis involving a careful characterization of the measurand with respect to all known influence quantities is presented. We point out several advanced methods for solar simulator characterization to determine related uncertainties on I_{STC} measurements of industrial solar cells. We applied these methods on a commercially available laboratory flasher. The thorough analysis of uncertainties of the utilized array spectroradiometer turns out to be of crucial importance. Flasher characterization beyond the state-of-the-art contains measurements of non-uniformity and temporal stability in spectral irradiance, cosine response of the detector, multiple reflections and the consideration of diffuse irradiation. A Monte Carlo method according to the Guide to the Expression of Uncertainty in Measurement (GUM) illustrates limits in accuracy of the investigated measurement instrumentation. Detailed results obtained for the investigated flasher are presented.

Keywords: Performance, solar simulator, array spectroradiometer, calibration, traceability, experimental methods

1 INTRODUCTION

For comparability of solar cell efficiency measurements the accurate determination of the short circuit current under standard test conditions (I_{STC}) is essential [1]. The photocurrent is directly related to the incident irradiance on the solar cell. For irradiating the solar cell, pulsed solar simulators (flashers) are commonly used in production as well as in laboratories.

Due to technical limitations solar simulators cannot exactly provide standard test conditions (STC). Corrections of possible deviations to STC need to be applied to increase accuracy in measurement. In order to correct for the difference between the spectral irradiance distribution of solar simulators and STC conditions, calibrated reference solar cells which are traceable to national standards are used as radiometric standards to adjust the irradiance levels in solar simulators. Subsequently a device under test solar cell (DUT) is tested preferably under the same irradiation. To indicate a standard measurement uncertainty $u(I_{STC})$, the lateral and spectral distribution of the simulated solar irradiation and properties of the utilized reference and DUT solar cells have to be taken into account. Usually the dimensions of industrial silicon solar cells differ from those of reference solar cells (WPVS-design with an active area of 20 x 20 mm²). A time consuming primary calibration (e.g. using the differential spectral responsivity method DSR [2]) of these small sized reference solar cells is transferred to larger solar cells with areas up to 200 x 200 mm² with a secondary calibration using high-accuracy solar simulators. With continuous solar simulators expanded measurement uncertainties (k=2) of 1.8 to 2 % are achieved for secondary I_{STC} calibrations [3], [4].

The purpose of a public-private cooperation between the company h.a.l.m. elektronik GmbH and Germanys national metrology institute Physikalisch-Technische Bundesanstalt (PTB) is to analyze a flashers capability to perform traceable I_{STC} measurements of large area solar cells. This task of secondary calibrations essentially requires a thorough analysis of all ingoing uncertainties in an analog way as performed for primary calibrations of reference solar cells. The optical set-up of the investigated laboratory flasher cetisPV-Celltest3 is thereby almost identical to h.a.l.m. solar cell testers used by manufacturers for production lines.

A comprehensive investigation of spectroradiometric measuring instrumentation was carried out in order to enumerate quantities for measurement uncertainties of individual uncertainty components of a flasher calibrated industrial solar cell.

The irradiated area of a pulsed solar simulator was systematically characterized with a suitable compact array spectroradiometer. Thereby the temporal, spectral, lateral and angular distribution as well as diffuse and reflective components of irradiation were considered.

Combining spectral uncertainties requires the consideration of wavelength-dependent uncertainties for calculating a spectral mismatch uncertainty [5].

A computer-based sensitivity analysis for secondary I_{STC} solar cell calibration using the examined pulsed laboratory flasher was performed. Besides optical properties, other important influence quantities, regarding characteristics of different sample solar cells, the measurement set-up and correlations were factored in to extend the uncertainty analysis.

2 PERFORMANCE REQUIREMENTS FOR SOLAR SIMULATORS

International standards describe testing procedures to classify elementary optical properties of solar simulators to increase comparability and to improve quality assurance for PV device performance testing [6], [7], [8]. Requirements stipulated by these standards rate the quality of test conditions compared to STC. Classification into categories (class A, B, C or “no class”) of solar simulator performance primarily aims at a classification of usability of testers in production environment but is not sufficient to derive individual measurement uncertainties. Explanatory notes in the standards demand some additional information about properties of simulated irradiation possibly effecting spectral measurements and corrections [9]. Strictly spoken, beside the consideration of non-uniformity and temporal stability of irradiance and spectral irradiance for spectral mismatch correction, additional influence quantities need to be examined individually to study their effects. A comprehensive measurement uncertainty analysis according to the Guide to the Expression of Uncertainty in Measurement (GUM) requires the consideration of all influence quantities and their corresponding measurement uncertainty.

The additional influence quantities for secondary calibration of $I_{\mathrm{STC,\ DUT}}$ using solar simulators are in particular given by:

- Characterization of the spectral irradiation conditions in the flasher with an *array spectroradiometer* and its measurement uncertainty for a subsequent mismatch correction. The influence of the following effects should be carefully analyzed and corrected when measuring solar simulator spectra [10]:
  - radiometric *calibration of spectral irradiance* responsivity with a standard lamp including estimation of the instrumental *stability*,
  - *wavelength calibration* using, e.g., atomic emission lines provided by pencil-type lamps,
  - *linearity* of the detector depending on irradiance levels and integration times,
  - *spectral stray light* within the instrument,
  - *angular response* of the entrance optics [11],
  - *timing* of the spectral measurement during short flash pulses.
- Temporal stability of spectral irradiance $E_{\lambda,\mathrm{sim}}(\lambda,t)$ of the simulator,
- Spatial non-uniformity of spectral irradiance,
- Influence of multiple reflections r_{cell} between solar cell and solar simulator optics [12][13],
- Angular distribution irradiation on solar cells surface and corresponding part of spectral irradiance
- Uncertainties in relative spectral responsivity s_{cell} of the reference and device under test solar cells
- Positioning of the solar cell and uncertainties due to offset to the measurement plane [14],
- Temperature measurement ΔT_{cell} and temperature coefficient α_{cell},
- Measuring equipment of electrical quantities (e.g. *I*-*V*-curvetracer, or DMM and shunt resistance).

3 MODEL OF A SOLAR CELL CALIBRATION UNDER SIMULATED SUNLIGHT

A mathematical model describing the measurement is recommended to compute the corresponding combined measurement uncertainty according to GUM. A secondary I_{STC} calibration with solar simulators can be treated as a substitution method of measurement using reference cells and a monitor device. Without appliance of several corrections due to deviations to standard testing conditions the calibration procedure can be summarized as follows:

In a first step the solar simulators irradiance is adjusted to the calibration value $I_{\mathrm{STC,ref}}$ of the reference solar cell. The ratio of the measured short circuit currents of the reference solar cell $I_{\mathrm{meas,ref}}$ to the monitor signal $I_{\mathrm{mon,ref}}$ defines this adjustment. Subsequently in a second step the short circuit current of the device under test solar cell $I_{\mathrm{meas,DUT}}$ is measured under irradiation with an irradiance level of $I_{\mathrm{mon,DUT}}$ (see Fig. 1).

Equation 3.1 expresses this relation assuming high linearity of the solar cells and the monitor detector. It allows to calculate short circuit current of the DUT including corrections for deviation from STC.

$$I_{\mathrm{STC,DUT}} = I_{\mathrm{STC,ref}} \cdot \frac{I_{\mathrm{meas,DUT}} / I_{\mathrm{mon,DUT}}}{I_{\mathrm{meas,ref}} / I_{\mathrm{mon,ref}}} \cdot \prod_i f_i \tag{3.1}$$

By applying correction factors f_i all known influences will be considered. These are given corresponding to the listed influences in section 2 by the following equation:

$$\prod_i f_i = f_M \cdot f_{T_{\mathrm{ref}}} \cdot f_{T_{\mathrm{DUT}}} \cdot f_{\mathrm{nu}} \cdot f_{\mathrm{refl}} \cdot f_{\mathrm{pos}} \tag{3.2}$$

Where f_{M} is the spectral mismatch correction given in [9]

$$f_M = \frac{1}{M} = \frac{\int_\lambda E_{\lambda,\mathrm{sim}}(\lambda)\, s_{\mathrm{ref}}(\lambda)\, \mathrm{d}\lambda}{\int_\lambda E_{\lambda,\mathrm{STC}}(\lambda)\, s_{\mathrm{ref}}(\lambda)\, \mathrm{d}\lambda} \frac{\int_\lambda E_{\lambda,\mathrm{STC}}(\lambda)\, s_{\mathrm{DUT}}(\lambda)\, \mathrm{d}\lambda}{\int_\lambda E_{\lambda,\mathrm{sim}}(\lambda)\, s_{\mathrm{DUT}}(\lambda)\, \mathrm{d}\lambda} \tag{3.3}$$

$f_{T^{\mathrm{ref}}}$ and $f_{T^{\mathrm{DUT}}}$ are the temperature correction factors defined by

$$f_{T_{\mathrm{ref}}} = \frac{1 - \Delta T_{\mathrm{mon,ref}}\, \alpha_{\mathrm{mon}}}{1 - \Delta T_{\mathrm{ref}}\, \alpha_{\mathrm{ref}}} \text{ and} \tag{3.4}$$

$$f_{T_{\mathrm{DUT}}} = \frac{1 - \Delta T_{\mathrm{DUT}}\, \alpha_{\mathrm{DUT}}}{1 - \Delta T_{\mathrm{mon,DUT}}\, \alpha_{\mathrm{mon}}}$$

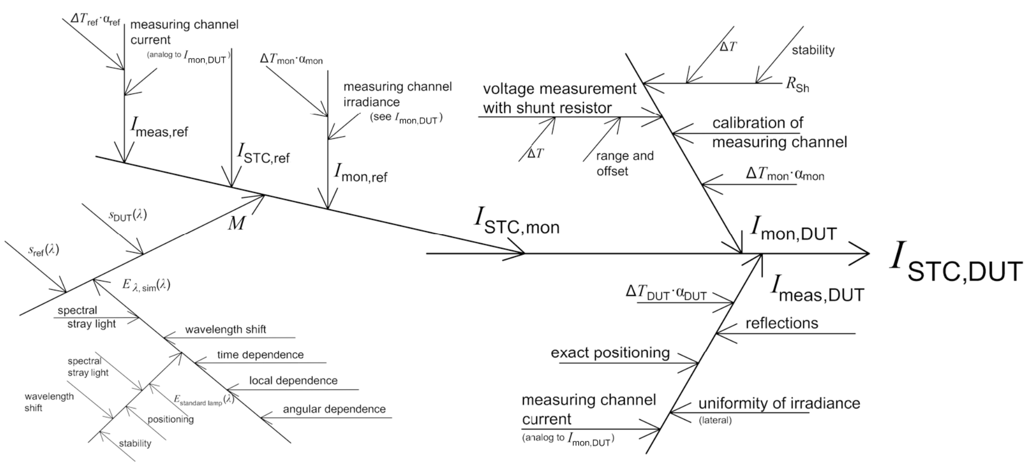

Figure 1: Scheme of contributing influence quantities for secondary I_{STC} calibration measurements of large area solar cells under simulated sunlight based on a substitution method of measurement with a monitor device.

Assuming solar cells of different sizes $A_{\mathrm{DUT}} \neq A_{\mathrm{ref}}$ with spatially homogenous spectral responsivities, the correction factor for the irradiance non-uniformity writes

$$f_{\mathrm{nu}} = \frac{A_{\mathrm{DUT}} \int_{A_{\mathrm{ref}}} E(x,y)\mathrm{d}x\,\mathrm{d}y}{A_{\mathrm{ref}} \int_{A_{\mathrm{DUT}}} E(x,y)\mathrm{d}x\,\mathrm{d}y} \quad (3.5)$$

.

Multiple reflections are summarized in

$$f_{\mathrm{refl}} = \frac{1 - r_{\mathrm{DUT}}}{1 - r_{\mathrm{ref}}} \quad (3.6)$$

where r_{cell} describe contributions of the irradiance which are reflected between the solar simulator optics and the particular solar cell. Differing reflectances may cause an increase in the measured short circuit current.

To consider deviations $\Delta z = z_{\mathrm{DTU}} - z_{\mathrm{ref}}$ of the distances from the different solar cells to the radiant source a correction factor f_{pos} has to be applied:

$$f_{\mathrm{pos}} = \frac{(z_{\mathrm{ref}} + \Delta z)^2}{{z_{\mathrm{ref}}}^2} = 1 + \frac{2 \cdot z_{\mathrm{ref}} \cdot \Delta z}{{z_{\mathrm{ref}}}^2} + \frac{\Delta z^2}{{z_{\mathrm{ref}}}^2}$$

It turns out for most flasher systems $\Delta z \ll z_{\mathrm{ref}}$ is a good approximation for a precise adjustment of the solar cells. Hence

$$f_{\mathrm{pos}} \approx 1 + \frac{2 \cdot \Delta z}{z_{\mathrm{ref}}} \quad (3.7)$$

is used for the correction.

4 RADIOMETRIC CHARACTERIZATIONS USING AN ARRAY SPECTRORADIOMETER

In order to correct for the spectral mismatch *M*, among other influences it is necessary to focus on the reliability of the spectral irradiance measurement which is usually carried out with an array spectroradiometer. All instrument properties of the spectroradiometer (as listed in section 2) were therefore investigated to perform traceable measurements with lowest uncertainties. Here we focus on two important properties of the measuring equipment, which are rarely taken into account in spectral irradiance measurements of solar simulators:

4.1 Spectral stray light

The calibration standard of spectral irradiance is usually a tungsten halogen lamp with a spectral irradiance distribution differing totally from xenon-based solar simulators. It turns out, that different spectral characteristics of the light sources are of crucial importance, due to the fact, that array spectroradiometers feature a poor suppression of internal spectral stray light. To correct for this effect, we applied a stray light correction matrix method which was published in prior work [15]. The stray light characterization of the array spectroradiometer used was carried out at PTB's tunable laser set-up PLACOS [16].

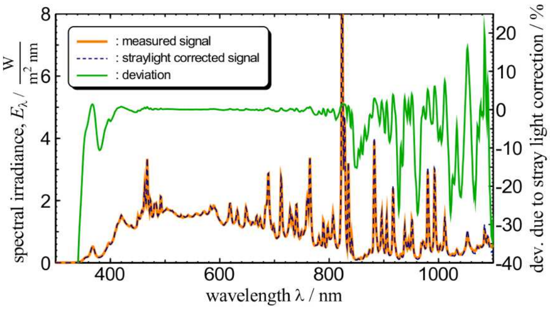

Figure 2: Impact of numerical stray light correction method on the measured spectrum of the investigated solar simulator.

The observed deviation in the measured solar simulator spectrum caused by the stray light (see Figure 2) affects directly the spectral mismatch *M* (see equation 3.3). The spectral stray light induces an error of about 0.1 % in the calculated spectral mismatch *M* which contributes directly to total measurement uncertainty.

4.2 Cosine response of the entrance optics

Consideration of irradiance uniformity is vital for high-accuracy flasher measurements. In many cases the distributed spectral irradiance is a function of the position upon the designated test area. By applying an array spectroradiometer in the radiation field it is possible to gather spatially resolved information on the spectral irradiance uniformity. Compared to integral detectors, such as photodiodes or solar cells, uncertainties in the uniformity measurement procedure due to spectral mismatch are taken into account and therefore corrected. In addition, the cosine response of the entrance optics (e.g. integrating sphere) should be considered and corrected. The cosine response of the integrating sphere employed as entrance optics of the spectroradiometer was determined by using a monitor stabilized tungsten halogen lamp and a fully automated ϑ-φ-goniometer. The results are shown in Fig. 3.

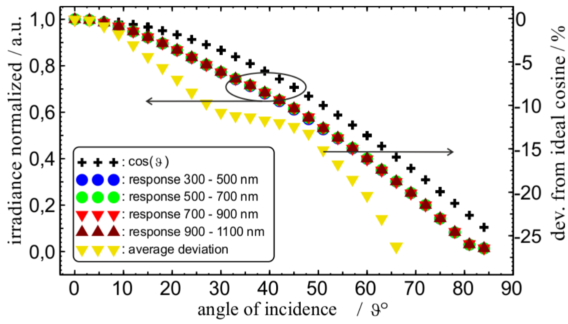

Figure 3: The measured signal of the array spectroradiometer is integrated over wavelength intervals and then normalized to the value at perpendicular angle of incidence.

To ensure that spectrally dependent influences in the angular response are considered as well, an evaluation of the angular response measurement was performed for different wavelength intervals. With the observed deviation, a correction for angular response differing from those of a lambertian surface is approached. The correction method obtained enables the consideration of different angles of incidence in a first approach when measuring solar simulators spectral irradiance, at different locations in the test area.

5 CHARACTERIZATION MEASUREMENTS ON OPTICAL PROPERTIES OF A FLASHER

To study the influences listed in section 2 a thoroughly characterized array spectroradiometer was used for the radiometric measurements of a pulsed laboratory solar simulator system of type cetisPV-Celltest3 by h.a.l.m.

5.1 Spatial non-uniformity of spectral irradiance

The determination of the non-uniformity of the investigated flasher's irradiance was carried out by using an array spectroradiometer with the examined integrating sphere as entrance optics. A 200x200 mm² sized area was probed at 25 different positions by *x*-*y* scanning with the entrance optics. The intensity of the flash pulse was monitored with a monitor detector at a fixed position. A cosine correction to account for the angular response of the entrance optics is performed using the deviation displayed in Fig. 3 as a correction. Therefore the mean angle of incidence ϑ is calculated under consideration of a trigonometric relation between distance of the test area z and the positions *x* and *y* of the detector (see Fig. 4).

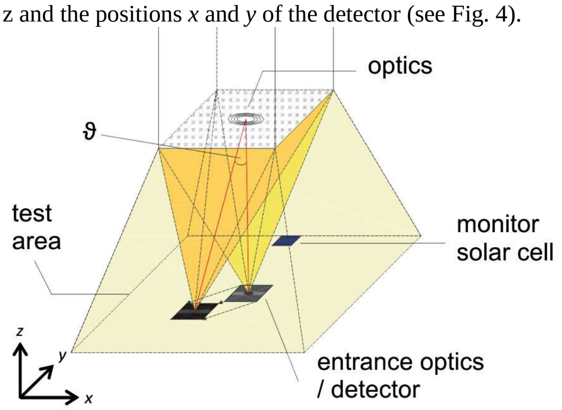

Figure 4: Scanning measurement procedure for the determination of non-uniformity of a h.a.l.m. flasher. With an averaged angle of incidence ϑ the cosine response of the detector was corrected in a first approach.

Without appliance of the cosine correction the measured irradiance at positions differing from the center would be underestimated (see Fig. 5). This relation leads to a systematic overestimation of the non-uniformity and thus to an increase of total measurement uncertainty.

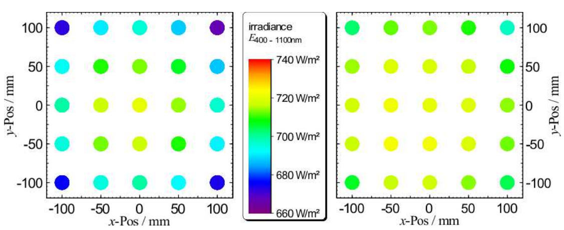

Figure 5: Non-uniformity map of the irradiance shows (left) the measured uncorrected irradiance and (right) the measured and cosine corrected irradiance within a wavelength interval from 400 nm to 1100 nm.

Diffuse components of the solar simulators irradiation are still underestimated with this simple method. The cosine correction can therefore only be a first approach with a point light source approximation. For a more detailed model, the angular distribution of the extended radiant source has also to be considered at any measured position in the test area (see section 5.5). For a cosine correction covering angular irradiance distribution on the entire test area, insufficient data points were available.

In addition influences of reflective components within the investigated flasher are depending on the scanning position. Thus, they affect the array spectroradiometer measurement and the measurement of the monitor signal contributing to uncertainty of this method of measurement.

5.2 Spatial non-uniformity of spectral mismatch

For an advanced understanding of the irradiance distribution it is necessary to consider the impact of spectral mismatch as function of the position. Therefore, we analyzed the measured data from the subsection above respecting spectral shifts between 300 nm and 1100 nm. As an example we calculated the spectral mismatch for two detectors, with the spectral responsivity of a crystalline silicon reference solar cell (see Fig. 11) and a thermal detector, which responds constantly relating to the spectrum (see Fig. 6). The spectral mismatch as a function of the position $M(x, y)$ illustrates spectral influences when using an integral method for measuring irradiance non-uniformity (e.g. with a solar cell as an integrating detector).

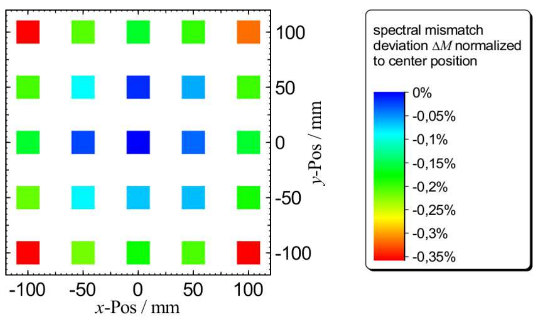

Figure 6: Influence of spectral shifts as a function of the position on spectral mismatch $M(x, y)$. The graph shows deviations $\Delta M(x, y)$ from $M(0, 0)$ at the center of the test area.

Deviations of up to 0.35 % in spectral mismatch were calculated for the case that spectral irradiance non-uniformity of this system remains unconsidered. A non-uniformity of spectral mismatch has to be taken into account for large area solar cell calibrations. Thus an average spectral mismatch correction factor was used for calculations with equation 3.3.

5.3 Temporal stability of spectral irradiance

Commonly in I_{STC} measurement set-ups a monitor solar cell is applied to the correction of temporal fluctuations of solar simulators irradiance. Transient-caused changes in the spectral irradiance distribution of flashers during a single flash pulse are therefore usually not considered. They may cause time dependence in the spectral distribution (e.g. due to the heating of the flash lamp during the ignition phase).

To quantify temporal effects of the solar simulator spectrum, measurements on repeating 110 ms flash pulses were performed by variation of the spectroradiometer trigger delay with an increment of

5 ms. The spectroradiometer's integration time was adjusted to 15 ms. For each timing delay 10 acquisitions with a defined repetition rate of 1/20 flash pulses per second were performed. In Fig. 7 a temporal shift in the spectral mismatch classification *MM* [6] is pictured. Results presented here illustrate the advantages of a long flash duration. When measuring the short circuit current of solar cells with this flasher within a timing interval between 35 ms and 85 ms, the contribution to uncertainty due to a spectral shift of the flash lamp is negligible. This relation has to be investigated individually for differing solar simulator lamp types including aging effects.

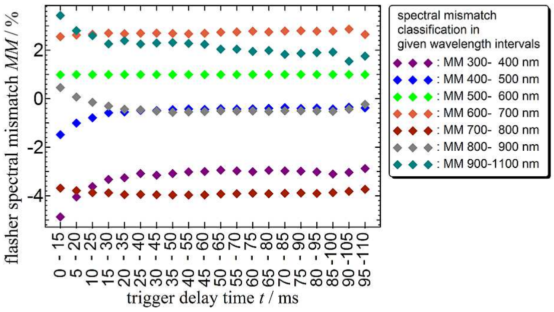

Figure 7: Temporal shift of a long pulse flashers spectral irradiance distribution. The flashers spectral mismatch *MM* is calculated analogue to procedures given in [6], but here in addition with a wavelength interval between 300 nm and 400 nm. The acquisition time of the array spectroradiometer was adjusted to 15 ms.

5.4 Multiple reflections

Reflections between solar cell and solar simulator optics occur in most solar simulators. For the case that reflectances of the reference and device under test (DUT) solar cells are differing, they need to be considered as a contribution to uncertainty. As an effect of a more reflective DUT-solar cell compared to the reference solar cell, the effective irradiance level of the flash lamp decreases automatically due to regulating process. By changing the operating point of the lamp, a shift in the flashers spectral irradiance can be expected. As a consequence undefined reflectances lead to a tremendous systematic influence on I_{STC} for the investigated system.

Usually the reflectance of built-in materials of a flashers test chamber is kept as low as possible. Reflectances of contacting chuck, probes, solar cells surfaces and housing, reflectors and optical filters are differing in particular. As its individual values must be assumed to be unknown, modifications on the flashers set-up inside the test chamber were used to expose measurable changes in the irradiance.

To investigate multiple reflections between solar cell and solar simulator optics a boundary check was performed using the h.a.l.m. cetisPV-Celltest3 and a solar cell contacting system cetisPV-Contact1. Therefore, 3 different scenarios were evoked by varying the reflective property of the irradiated plane in comparison to regular operation conditions. The change in irradiance was determined using a monitor solar cell without regulating the flasher's irradiance level. As a worst case scenario a highly reflective mirror was positioned in the irradiated plane instead of a large area solar cell. For the best case scenario black absorption material was used. Regular operation conditions are defined as a scenario with the uncovered contacting. We compared the measured irradiances for different reflective scenarios. Deviations between best/worst case proceeding from a regular measurement situation are shown in Table I.

Table I: Effect of multiple reflections within the cetisPV-Celltest3

Scenario	worst	best	regular
Irradiance level / W/m²:	960.8	927.1	931.8
Dev. to regular scenario due to reflection / %:	3.1	- 0.5	---

An appropriate estimation of the reflectance of c-Si solar cells leads to values less than 20%. Compared to the worst case in this study, the sum of multiple reflective irradiation parts within the flasher using a crystalline silicon solar cell lead to an increase of about 0.5 % in the irradiance. For the case, that reflectance's have to be estimated, we accept that high uncertainties propagate through to combined uncertainty.

5.5 Angular distribution of irradiance:

In order to determine a solar simulator spectral irradiance distribution, the flasher should be regarded as an extended radiant source. Similar to its natural archetype, the investigated solar simulators irradiation contains beside a direct component also a substantial amount of diffuse irradiation. Compared to set-ups for primary solar cell calibration in laboratories, where usually only direct (collimated) irradiation is assured, most solar simulator types feature diffuse components. When considering this angular irradiance distribution, a decrease of uncertainty in I_{STC} measurements can be expected [17].

To measure the angular change of this condition, we used a scanning method to determine the inclined irradiation on a solar simulators test area. Therefore we modified the entrance optics of the array spectroradiometer by using a collimating aperture tube. With a given aperture a defined solid angle can be inspected (see Fig. 8). Then the investigated radiometric quantity is the radiance L measured in W m^{-2} sr^{-1}.

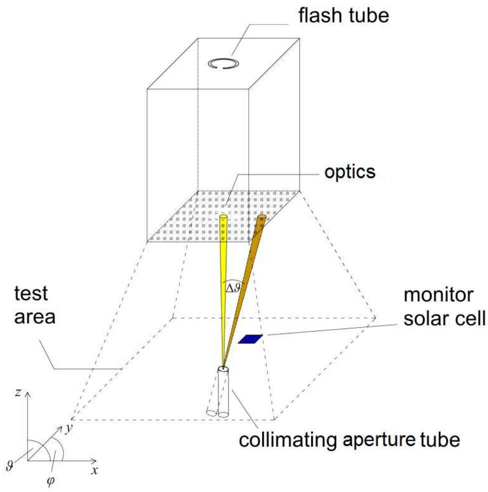

Figure 8: Measurement method for the determination of the angular resolution of the inclining irradiation on a solar cell.

The estimation of direct and diffuse solar radiance components was performed by mounting the aperture tube on a 2-axis goniometer. At the center of the test area, the half space facing towards the flasher's radiant source was scanned with an aperture angle of 3° (see Fig. 9).

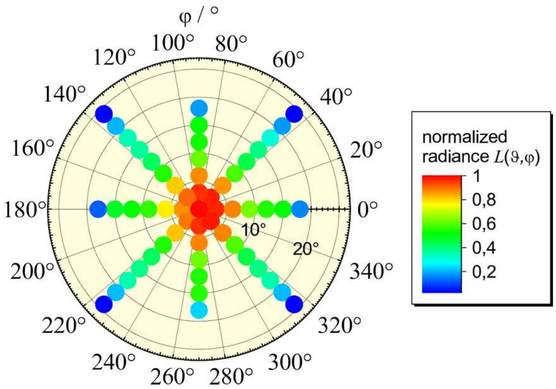

Figure 9: The angular resolved radiance distribution $L(\vartheta, \varphi)$ measured at the center of the flashers test area. The lowest values measured for ϑ represent the outer dimensions of the flasher optics at a given distance z.

Thus, measured radiance $L(\vartheta, \varphi)$ enhances the description of the converted solar irradiation into a short circuit current I_{SC} by adding angular resolved information of the source and the detector. Spectrally resolved this theoretical approach writes:

$$I_{\mathrm{SC}} = \int_{\lambda} \iint_{\Omega} L_{\lambda}(\lambda, \vartheta, \varphi) \cdot s(\lambda, \vartheta, \varphi) \cdot \cos\vartheta \, \mathrm{d}\Omega \, \mathrm{d}\lambda \qquad (5.1)$$

with the solid angle Ω defined by

$$\Omega = \sin\vartheta \, \mathrm{d}\vartheta \, \mathrm{d}\varphi$$

and the solar cells angular spectral responsivitiy $s(\lambda, \vartheta, \varphi)$.

An evaluation of this model regarding spectral mismatch M requires additional data of the solar cell's angular spectral responsivity $s(\lambda, \vartheta, \varphi)$ and angular information on the reference solar spectrum. With the consideration of angular dependencies, an advanced understanding of integral measurement methods for solar cells under simulated and natural sunlight is expected.

6 MEASURMENT UNCERTAINTY CALCULATION

The determination of a combined standard uncertainty $u(I_{\mathrm{STC,DUT}})$ requires a careful analysis under consideration uncertainty propagation according to GUM. Previously published work shows, that wavelength-dependent uncertainties are not negligible for uncertainty analysis [5, 19]. Analog to Hohl-Ebinger and Warta we used a Monte Carlo method for uncertainty computation. The spectral mismatch M is therefore calculated including correlated and wavelength-dependent uncertainties of the solar cell's spectral responsivities and the flasher's spectral irradiance measurement (see equation 3.3).

A sensitivity analysis of the array spectroradiometer's wavelength uncertainty $u_{\Delta\lambda}(E_{\lambda,\mathrm{sim}}(\lambda))$ was performed by calculating different uncertainties with a wavelength offset $\Delta\lambda$ in the range of ±0 nm to ±0.5 nm. As a practical approach we calculated the wavelength-dependent contributions to the uncertainty of the measured flasher spectrum as follows:

$$u_{\Delta\lambda}\left(E_{\lambda,\mathrm{sim}}(\lambda)\right) \approx \left|\frac{E_{\lambda,\mathrm{sim}}(\lambda + \Delta\lambda) - E_{\lambda,\mathrm{sim}}(\lambda - \Delta\lambda)}{2\,\Delta\lambda}\right| \cdot \Delta\lambda \qquad (6.1)$$

Besides wavelength-dependent uncertainties, also contributions resulting from spectral irradiance calibration with a standard lamp, statistics and other instrument properties ("type B"-uncertainties) are considered in the combined uncertainty $u(E_{,\mathrm{sim}}(\lambda))$.

As an example a variety of spectral mismatch M was calculated with a combination of two spectral responsivities (unfiltered c-Si and filtered c-Si) of primary calibrated reference solar cells with lowest measurement uncertainties (see Fig. 10). An increase in spectral mismatch uncertainty is observed for higher wavelength offset. Using an interferometric characterization method a reduction of wavelength uncertainty is expected. This approach is published in other work [18]. For further investigation of uncertainties a wavelength offset was taken from technical specification ($\Delta\lambda$ = 0 nm ± 0.3 nm) of the array spectroradiometer, which includes also long term stability of the wavelength calibration.

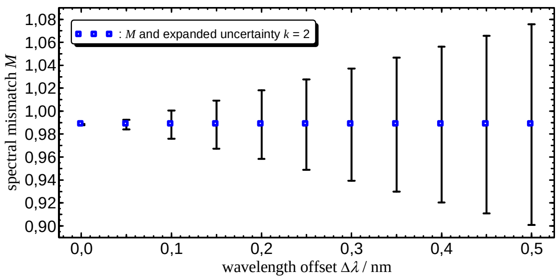

Figure 10: Impact of array spectroradiometer's wavelength uncertainty on spectral mismatch uncertainty. The calculation was done using relative spectral responsivities of a set of primary calibrated unfiltered c-Si and filtered c-Si solar cells.

For the uncertainty calculation of an example calibration we used spectral responsivity data of a primarily calibrated reference solar cell from PTB and of a large area c-Si solar cell taken from literature, which was measured with a filter monochromator set-up [5].

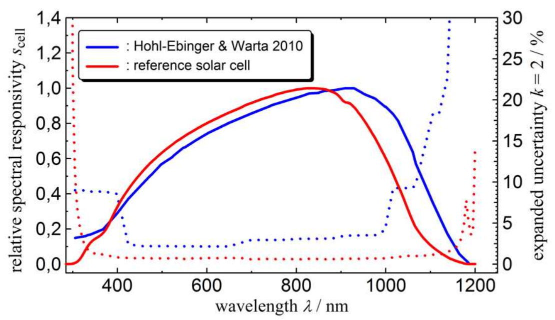

Figure 11: Relative spectral responsivities with their corresponding measurement uncertainties (dotted curves) used for combined uncertainty computation of a secondary I_{STC} flasher calibration measurement with a Monte Carlo method. Data from other work (blue curves) was used for the device under test solar cell [5].

The computation of spectral mismatch M and its corresponding standard uncertainty $u(M)$ with the quantified flasher's spectral irradiance within a wavelength interval between 300 nm and 1100 nm and solar cell responses given in Fig. 11 leads to a result of $M = 0.9872 \pm 0.0029$.
Additionally for this example, the contribution of spectral mismatch between 1100 nm and 1200 nm must be estimated for a complete analysis. The spectral mismatch correction factor contributes directly (see equation 3.3) in the total combined uncertainty $u(I_{STC,DUT})$.

In a next step a uncertainty analysis of all known influence quantities was performed. Therefore, we calculated a detailed measurement uncertainty according to equation 3.1 with focus on contributing influence quantities studied as presented above. Beside the measured optical quantities all other known influences were considered as shown in Fig. 1. A reasonable value for the measurement uncertainty for the non-uniformity of irradiance was chosen. The topic of this measurement procedure considering the entire diffuse irradiation components is subject of future investigations. For electrical and thermal influences we used "type B" standard uncertainties of the instruments calibration certificates for ideal laboratory conditions. Multiple reflections were determined by estimation with a boundary check (see section 5.5). Using these maximum values and assuming values of reflectances of the solar cells between 0 % and 20%, we derived uncertainties of multiple reflections within the investigated flasher. Hence we obtained a value of $r_{cell} = 0.005 \pm 0.005$. For the accuracy in positioning we assumed uncertainties of $\Delta z = 0 \pm 0.1$ mm.

Table II: Uncertainty budget of a large area (200x200 mm²) c-Si solar cell secondary I_{STC} calibration with a h.a.l.m. flasher and a 20x20 mm² reference solar cell in WPVS design.

Input quantity X_i	$u(y_i)$
Measurement DUT solar cell $I_{meas,DUT}$	0.004 %
Monitor signal $I_{mon,DUT}$	0.005 %
Calibration value $I_{STC,ref}$	0.286 %
Measurement ref. solar cell $I_{mon,ref}$	0.004 %
Monitor signal $I_{mon,ref}$	0.005 %
Spectral mismatch M	0.294 %
Temperature measurement $\Delta T_{mon,DUT}$	0.006 %
Temperature measurement ΔT_{ref}	0.006 %
Temperature measurement ΔT_{DUT}	0.008 %
Temperature measurement $\Delta T_{mon,ref}$	0.006 %
Non-uniformity of irradiance f_{nu}	0.565 %
Multiple reflections r_{DUT}	0.290 %
Multiple reflections r_{ref}	0.290 %
Positioning of the solar cells Δz	0.115 %
Combined standard uncertainty	0.817 %

The uncertainty analysis results in an expanded uncertainty of 1.63 % ($k = 2$) for a secondary calibration of an industrial c-Si solar cell with an area of 200x200 mm² under idealized laboratory conditions (see Table II). It turns out, that uncertainties in non-uniformity of irradiance, spectral mismatch and multiple reflections in the flasher are dominating the total uncertainty. We gained an advanced comprehension of I_{STC} flasher measurements regarding to radiometric properties. For obtaining a complete picture, a detailed characterization of the measurement instrumentations electronics, solar cell contacting and thermal conditions for solar cell performance measurements is required. This is also subject of future research.

7 CONCLUSION AND OUTLOOK

In our study, a detailed view on measurement uncertainty components for a secondary flasher calibration of industrial waver-based silicon solar cells is pictured. A measurement equation was derived for this model to compute the corresponding measurement uncertainty considering several observed uncertainty components.

Each contribution to the total measurement uncertainty was investigated individually to obtain a complete overview of the resulting uncertainty. We focused on radiometric characterization methods with array spectroradiometers for solar simulators. Therefore, advanced methods for the characterization of spectral composition and homogeneity were applied in addition to IEC 60904-9 Edition 2.0 (2007) requirements.

The thorough radiometric characterization of a solar simulator system performed in this work resulted in an advanced understanding of the uncertainty budget in I_{STC}. It was observed that a detailed characterization of the array spectroradiometer used for determining the spectral irradiance distribution is vital for the analysis of measurement uncertainties. A comprehensive estimate of uncertainty according to GUM has been performed for a combination of crystalline silicon reference and device under test solar cells.

With a sensitivity analysis we pointed out that wavelength-dependent uncertainties show a considerable impact on spectral mismatch, in particular for the use of filtered c-Si solar cells.

As a result of our research, a expanded uncertainty for an large area c-Si solar cell calibration of $U(I_{STC}) = 1.63$ % ($k = 2$) is calculated by considering enhanced methods for solar simulator characterization.

The Monte Carlo simulation revealed uniformity, spectral mismatch of the irradiation and reflections as dominating factors of the total measurement uncertainty. Our results demonstrate the importance of a systematic characterization of solar simulators, including the measurement equipment commonly used for this purpose. Our work covers a detailed description of known optical influences and a basic understanding of electrical and thermal influences. An entire analysis of all known influences is essential for secondary I_{STC} calibrations of solar cells. Experimental methods presented in this work are important for an advanced understanding of measurement uncertainties on the road towards traceable photovoltaic performance measurements with flashers.

8 ACKNOWLEDGEMENT

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