EMRP PHOTOCLASS: TOWARDS AN ENERGY-BASED PARAMETER FOR PHOTOVOLTAIC CLASSIFICATION

Report RMG 1

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Glossary

PTB	-	Physikalisch-Technische Bundesanstalt
LU	-	Loughborough University
EMRP	-	European Metrology Research Programme
RMG	-	Researcher Grant Contract
JRP	-	Joint Research Project
I_{STC}	-	Short circuit current under Standard Test Conditions
CREST	-	Centre for Renewable Energy Systems Technology
DSR	-	Differential Spectral Responsivity
STC	-	Standard Test Conditions
Mono c-Si	-	Mono crystalline Silicon
EU-PVSEC	-	European Photovoltaic Solar Energy Conference
DUT	-	Device under test
GUM	-	Guide to the Expression of Uncertainty in Measurement

Partners: **PTB,** LU
(Lead partner in bold)

Deadline: August 2015

Content

1. Objectives and research schedule of RMG 1

The present report of RMG 1 is a part of the JRP ENG55 ‘Towards an energy-based parameter for photovoltaic classification’ (PhotoClass).
The goals of RMG 1 is to perform calibration measurements of the short circuit current of reference solar cells under Standard Test Conditions (I_{STC}) [1] and spectral response (SR) from at least two solar cells using the polychromatic SR method and to produce an uncertainty budget of the polychromatic method used at the facility at CREST, LU. A set of two unfiltered and one filtered mono c-Si reference solar cells were calibrated, using the primary DSR method at PTB and the secondary polychromatic SR method at CREST. The intercomparison of the methods of measurement supports the knowledge transfer on the use of different solar cell calibration methods at PTB and LU. An enhanced understanding of the measurement uncertainty of the different calibration methods provides additional support for ENG 55.
This report contains the results of both calibration methods and a characterisation of the polychromatic SR facility for an estimation uncertainty budget (RMG deliverables **D1** and **D2**):

- At least two solar cells calibrated using the polychromatic SR solar cell calibration method
- Uncertainty budget prepared for the polychromatic SR method of solar cell calibration

I intend to publish the results of this intercomparison together with the Results of the RMG 2 at the European Photovoltaic Solar Energy Conference EU PVSEC 2017 or in the European Photovoltaic Solar Energy Conference EU PVSEC 2018 (**D3**). The quality of the presentation will benefit from the supplementary methods.
A brief summary of the research activities performed during the RMG 1 is presented at the JRP webpage (**D4**).
During the research stay at LU the RMG-Researcher received training lessons in performing polychromatic SR solar cell calibration method used at CREST from the LU-staff (**D5**). The RMG-Researcher intends to participate at the next JRP-meeting in September 2015 to present results of the reported work to all partners (**without Deliverable number**).

2. Description of calibration methods and measurement procedures

2.1. The DSR-Method at PTB

PTB realizes lowest measurement uncertainties for the calibration of the short circuit current under Standard Test Conditions (I_{STC}) of reference solar cells and serve as a qualified World Photovoltaic Scale (WPVS) laboratory [2]. The facilities of PTB are based on the successfully applied Differential Spectral Responsivity (DSR)-method [3] that allows the determination of the absolute spectral responsivity and nonlinearity of solar cells with the lowest uncertainties.
This method uses the combination of a modulated (quasi-) monochromatic beam and a white light (bias) source. The bias radiation (E_{Bias}) sets the solar cell into the working points. The corresponded DC output currents (I_{Bias}) are measured with a DC-multimeter. The modulated (quasi-) monochromatic radiations (E_{mono}) causes additional AC output currents (ΔI_{mono}) and are measured with a lock-in amplifier.
Than a comparison of the AC current of the reference solar cell under test with the AC current of a primary calibrated photodiode is performed, to determine the differential spectral responsivity $\tilde{s}(E_{\mathrm{Bias}}, \lambda)$ for each working point. It is defined as the slope of the function *I* over *E* (see equation (1)) [4]:

$$\tilde{s}(E_{\mathrm{Bias}}, \lambda) = \frac{\Delta I_{\mathrm{mono}}(E_{\mathrm{Bias}}, \lambda)}{\Delta E_{\mathrm{mono}}(\lambda)} \tag{1}$$

The differential form of this curve is then [4]:

$$\tilde{s}(E_{\mathrm{Bias}}, \lambda_0) = \left.\frac{\partial I_{\mathrm{bias}}(E, \lambda)}{\partial E(\lambda)}\right|_{E_{\mathrm{bias}}, \lambda_0} \tag{2}$$

The slope can be determined by the measured current I_{bias} divided by the irradiance E_{Bias} of the monochromatic radiation.
To calculate the I_{STC} and the absolute spectral responsivity $s_{\mathrm{STC}}(\lambda)$ under Standard Test Conditions (STC) the measured DSR $\tilde{s}$ is then weighted with the spectrum of the Standard Test Condition AM1.5G [5] (see equation (3) [4].

$$\tilde{s}_{\mathrm{AM1.5}}(E_{\mathrm{Bias}}) = \frac{\int_0^\infty \tilde{s}(E_{\mathrm{Bias}}, \lambda) \cdot E_{\lambda,\mathrm{AM1.5}}(\lambda)\, \mathrm{d}\lambda}{\int_0^\infty E_{\lambda,\mathrm{AM1.5}}(\lambda)\, \mathrm{d}\lambda} \tag{3}$$

For the irradiance under Standard Test Conditions $E_{\mathrm{STC}} = 1000\ \frac{\mathrm{W}}{\mathrm{m}^2}$ following relation is given [4]:

$$E_{\mathrm{STC}} = 1000 \frac{\mathrm{W}}{\mathrm{m}^2} = \int_0^{I_{\mathrm{STC}}} \frac{1}{\tilde{s}_{\mathrm{AM1.5}}(I(E_{\mathrm{Bias}}))} \mathrm{d}I \tag{4}$$

The determination of the desired calibration value, the I_{STC} is then calculated iteratively by increasing the upper integration limit in equation (4) until E_{STC} = 1000 W/m² is fulfilled. The absolute spectral responsivity $s_{\mathrm{STC}}(\lambda)$ of the measured device under STC is then [4]:

$$s_{\mathrm{STC}}(\lambda) = \frac{I_{\mathrm{STC}}}{\int_0^{I_{\mathrm{STC}}} \frac{\mathrm{d}I}{\tilde{s}\,(I_{\mathrm{Bias}}, \lambda)}} \qquad (5)$$

In a second step, the following calculation can be applied for cross-checking the I_{STC} [4]:

$$I_{\mathrm{STC}} = \int_{\lambda} E_{\lambda,\mathrm{STC}}(\lambda)\; s_{\mathrm{STC}}(\lambda)\; \mathrm{d}\lambda \qquad (6)$$

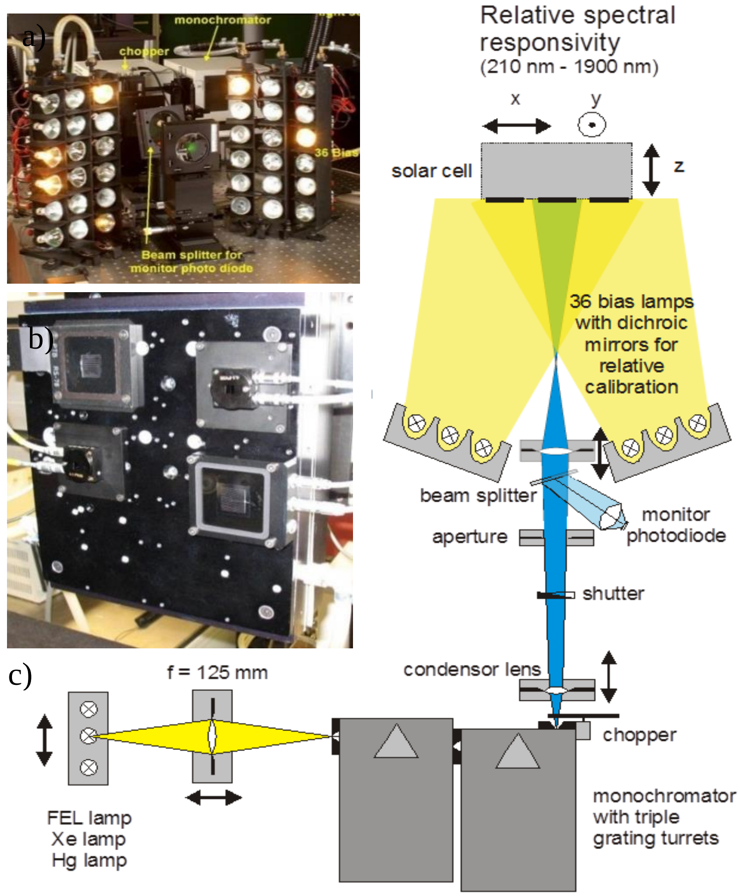
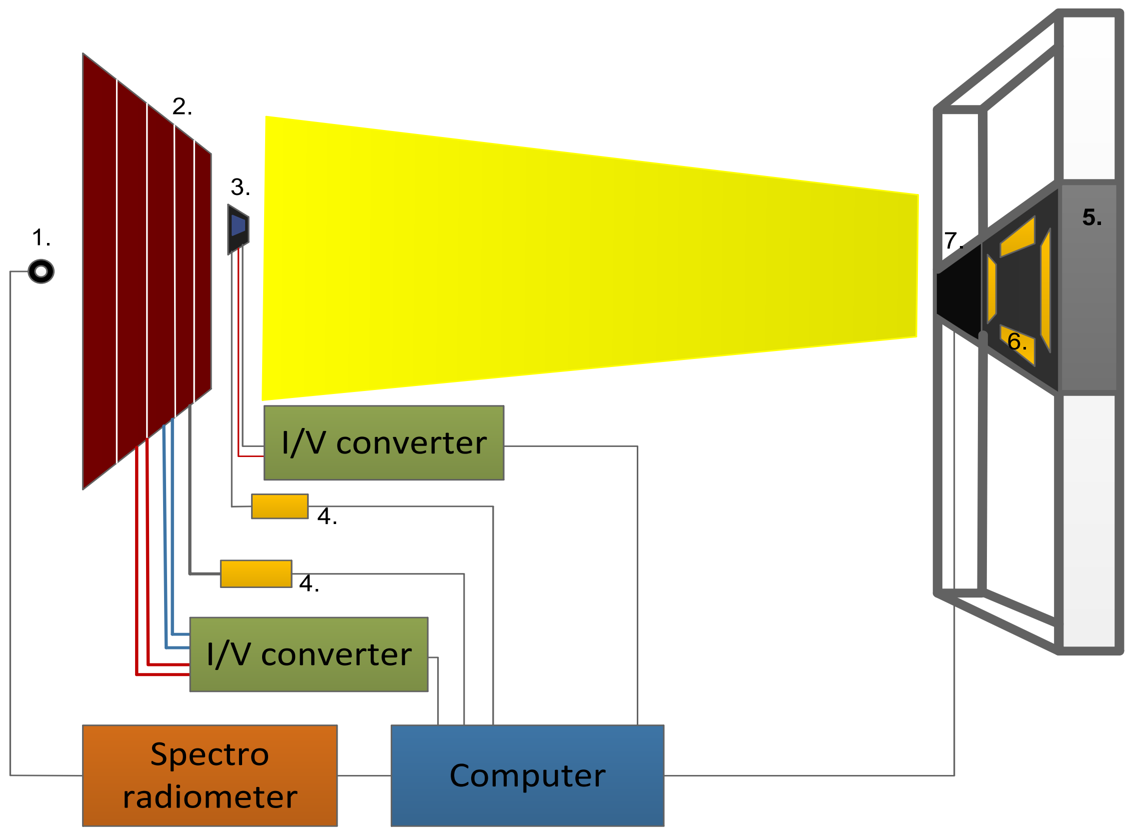


Figure 1: The DSR-Facility at PTB.
a) 36 halogen bias lamps are irradiating the solar cells at different operating conditions to consider non-linearity of the devices.
b) The solar cells and references are mounted on a movable temperature controlled sample holder.
c) Modulated (quasi-) monochromatic radiation is produced by different types of broadband lamps, a double-monochromator system and a chopper. Temporal instabilities during the measurement are compensated by a monitor photodiode [6].

2.2. The polychromatic determination of the spectral response (SR) at Loughborough University

The size of the calibrated solar cells with the DSR-method is limited by the signal to noise ratio due to the power of the (quasi-) monochromatic beam. CREST at LU (Centre for Renewable Energy Systems at Technology, Loughborough University) use a workaround. The LU uses a polychromatic spectral responsivity (SR)-facility to get a better signal to noise ratio. This is realized with a white light flasher and different optical filters. The SR can be calculated with the knowledge of the polychromatic spectra and the related currents. CREST use a PASAN 3b solar simulator as a white light flasher. It consists of a capacitor bank as a power supply, electronic load for data acquisition, and software for measurement control [7]. The spectra are measured by a modified EKO MS-700 spectroradiometer. The entrance optic and the device under test (DUT) have to be in the same measurement plane [7]. The setup is shown in Figure 2 and Figure 3.



1.Diffuser; 2. DUT; 3.Monitor cell; 4.Temperature sensor;
5.Xe lamp; 6.Polychromatic filters; 7.Filter cassette

Figure 2: The experimental setup for a large-area SR measurement using a new polychromatic SR fitting method [8]

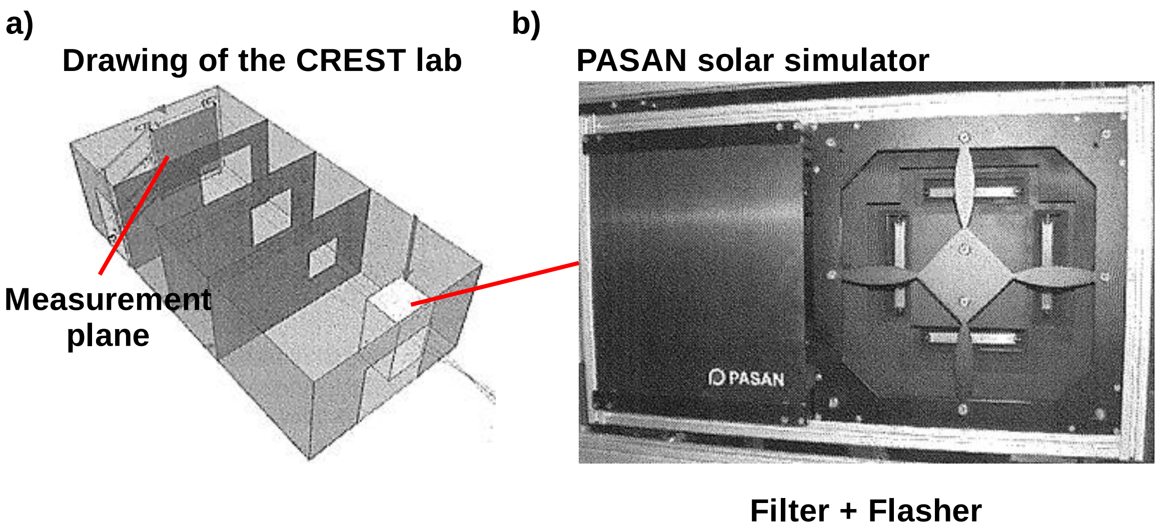


Figure 3: Layout of PASAN 3b solar simulator in use at CREST lab [7].

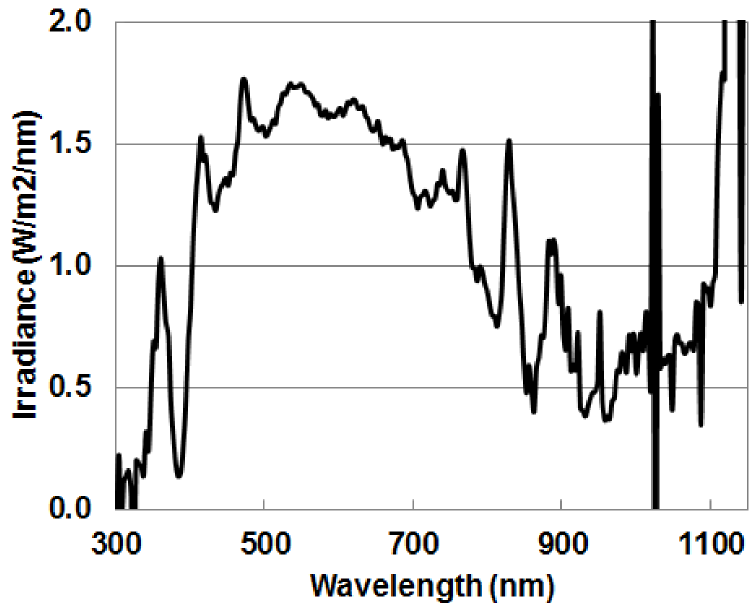
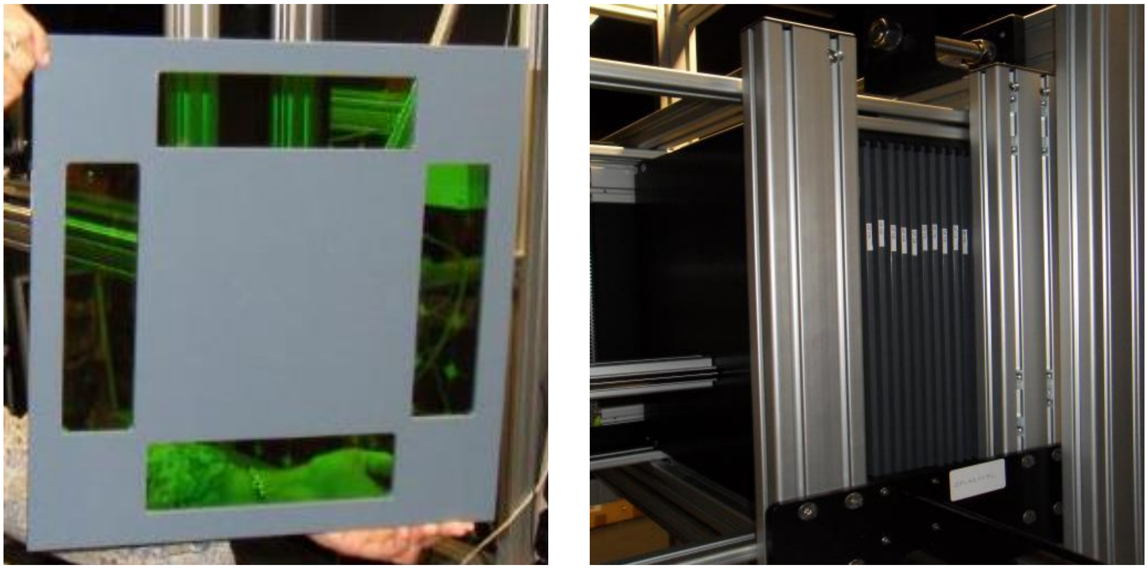


Figure 4: Spectral distribution of PASAN pulsed light [7].

The spectroradiometer measures the spectrum simultaneous to the *IV*-curve measurement of the DUT and the monitor cell by PASAN 3b. An example for the spectrum of the PASAN 3b is shown in Figure 4.

The spectrum of the Xenon lamp can be changed by polychromatic filters. The polychromatic filters are broadband filters with a well-defined spectral throughput. A set of broadband filters are integrated in the PASAN 3b filter cassette (see Figure 5). A few examples of resulting spectra are shown in Figure 6.



a. Individual Filter frame b. Filter cassette

Figure 5: Arrangement of a set of polychromatic filters in a filter cassette in the PASAN solar simulator system [8]

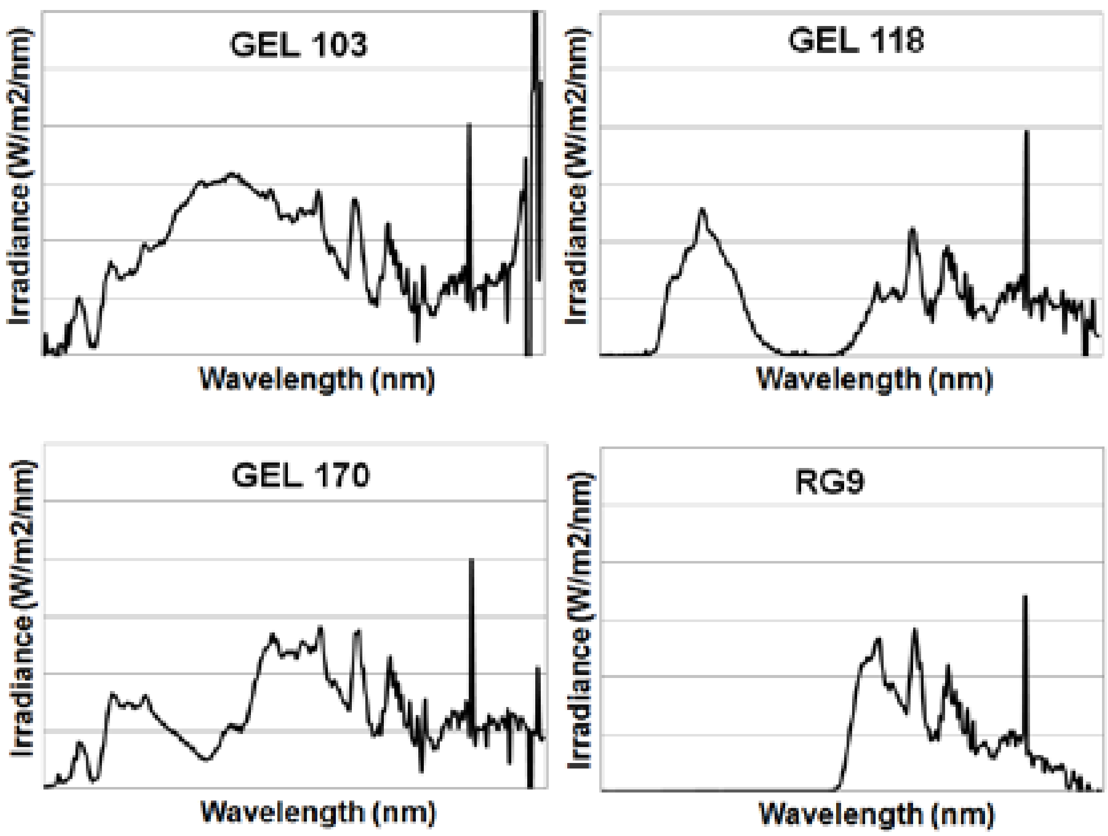


Figure 6: Variation of spectral distribution throughput of 4 example broadband filters [7]

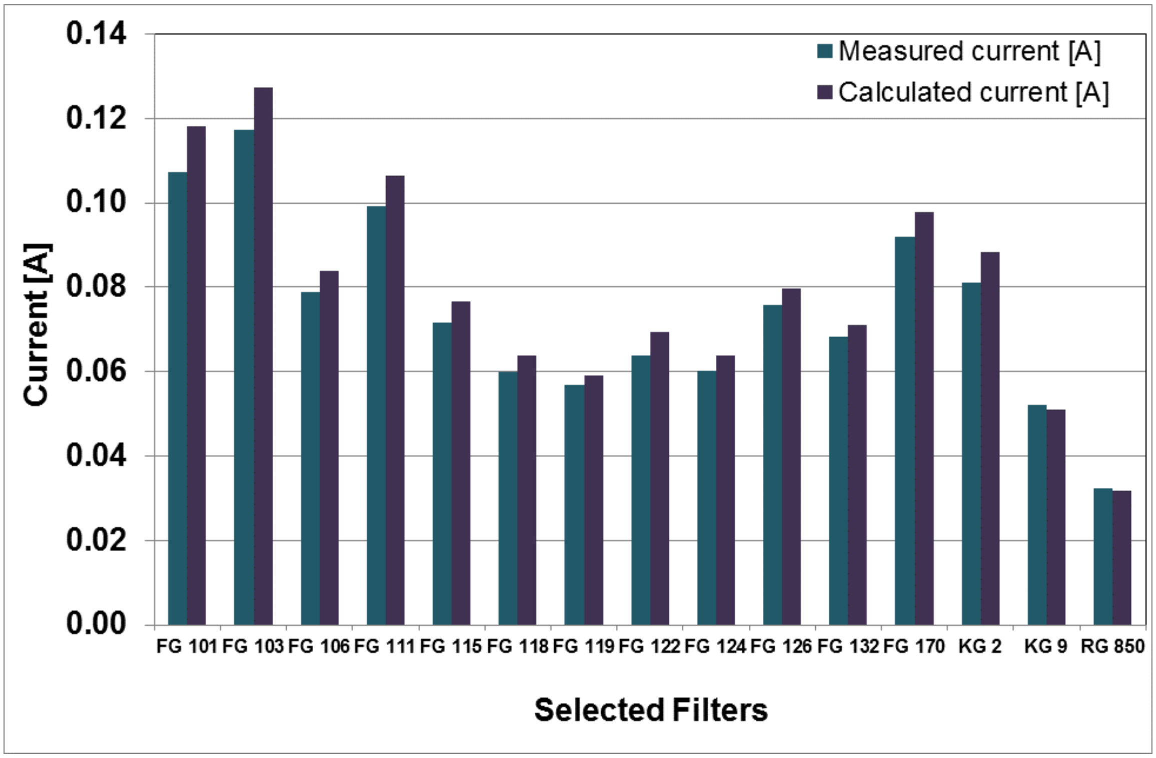


Figure 7: Comparison of the measured and calculated currents of a reference solar cell for all selected polychromatic filters [8]

The knowledge of the polychromatic spectra (E_{meas}) and the related currents (I_{meas}) is used to optimise a spectral responsivity model. For example a fifth order Gaussian distribution function can be chosen as a spectral responsivity ($s_{\mathrm{model}}(\lambda)$) [7].

$$s_{\mathrm{model}}(\lambda) = \sum_{i=1}^{5} a_i \exp\left[-\left(\frac{\lambda - b_i}{c_i}\right)^2\right] \quad (7)$$

where a_i, b_i and c_i are parameters of the Gaussian distributions. This simulated spectral responsivity (s_{model}) and the measured spectra are used to calculate estimated short circuit currents (I_{model}) in equation (8) [7],

$$I_{\mathrm{model}} = A \int_{\lambda_{min}}^{\lambda_{\mathrm{max}}} s_{\mathrm{model}} E_{\mathrm{meas}}\, \mathrm{d}\lambda \quad (8)$$

where A is the cell area of DUT, and λ_{min}, λ_{max} is the wavelength range of the spectroradiometer [7]. The calculated and the corresponding measured currents can be compared (see Figure 7). In a last step the parameters of the Gaussian distributions (a_i, b_i, c_i) have to be optimized with an iterative fitting algorithm in such a way that the difference between the calculated and the corresponding measured currents is conveniently

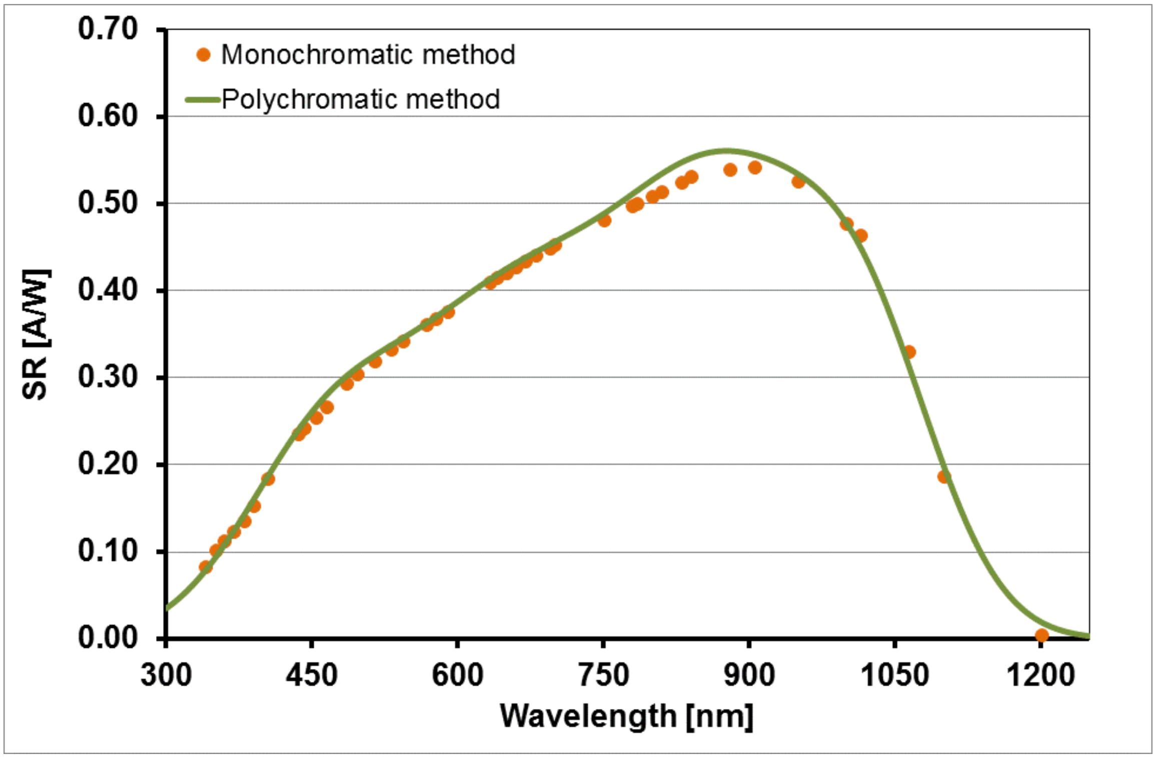


Figure 8: SR determination of a poly-crystalline PV device after the correction factor is applied [8]

minimized. The resulting simulated spectral responsivity should correlate with the real spectral responsivity (see Figure 8).

3. Calibration of reference solar cells

A set of two unfiltered and one filtered mono c-Si reference solar cells were calibrated, using the DSR method at PTB and the polychromatic spectral responsivity (SR) method at Loughborough University (LU) during the RMG. The List of calibrated reference solar cells is summarized in Table 1.

Table 1: List of used reference solar cells

ID	Technology	Size	Type
Sample #1	c-Si	(20x20) mm²	unfiltered / encapsulated and front glass
Sample #2	c-Si	(20x20) mm²	unfiltered / encapsulated and front glass
Sample #3	c-Si	(20x20) mm²	NIR filtered / encapsulated and front glass

3.1. Results with the DSR-method

The presented reference solar cells was calibrated at the DSR facility at PTB in accord with the DSR method (2.1). The results are summarized in Table 2.

Table 2: Results of the short-circuit currents under Standard Test Conditions (I_{STC}) with the DSR-method with corresponding expanded measurement uncertainty (k = 2)

ID	Calibration Date	Reference ID	I_{STC} / mA
Sample #1	22th February 2015	PV13&PV25	141,11 ± 0,74
Sample #2	23th February 2014	PV13&PV25	140,07 ± 0,74
Sample #3	3rd February 2015	PV13&PV25	35,70 ± 0,20 A

The uncertainty is calculated due to the Guide to the Expression of Uncertainty in Measurement (GUM) [6] (see Table 3).
The calibration value of solar cells is calculated with the equations shown in 2.1 when using the DSR-method. For that reason no contribution of measurement uncertainty of a solar spectrum has to be considered. As a consequence measurement uncertainty for spectrally filtered reference solar cell types is kept at the same level as for unfiltered devices.

Table 3: Uncertainty budget for reference solar cell calibration at PTB's DSR-facility [6]

Type A uncertainty: Uncertainty due to unstable cell temperature (± 0.5 K)	< 0,05 %
Type B uncertainties: Uncertainty of the standard detector(s)	< 0,1 %
Uncertainty due to nonlinear and/or narrow-band cells	< 0,05 %
Transfer uncertainties (repeatability) due to relative spectral responsivity absolute spectral responsivity at discrete wavelength(s) 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	0,05% 0,05% 0,2 %
Combined standard uncertainty (*k* =1)	**0.25 %**

3.2. Results with the polychromatic SR-method

The presented reference solar cells (Table 1) were also calibrated at the polychromatic SR-facility at LU in according to the polychromatic SR-method (section 2.2). The spectra are generated with the PASAN 3b and broadband filters, the spectra are measured with a modified EKO MS-700 and the corresponding *IV*-curves and consequently the short-circuit currents (I_{SC}) are measured with the PASAN 3b.
The generated spectra due to the used filter for the calibration of the Sample #3 reference solar cell are shown in Figure 9. The corresponding short-circuit currents are summarized in Table 4.
The polychromatic SR-facility at LU can't set an irradiance level as a working point, because it has only the typical PASAN 3b spectrum with additional filters with different transmission levels. Therefore the polychromatic SR-method is not useful to determine or study the nonlinearity of solar cells. This circumstance causes an additional uncertainty for non-linear solar cells.
The resulting simulated spectral responsivity (s_{model}) is optimized with an iterative fitting algorithm in such a way that the difference between the calculated and the corresponding measured currents is conveniently minimized. The received simulated spectral responsivity is shown in Figure 10 as a red line. The result of the DSR-method at PTB is shown as a black line for comparison.

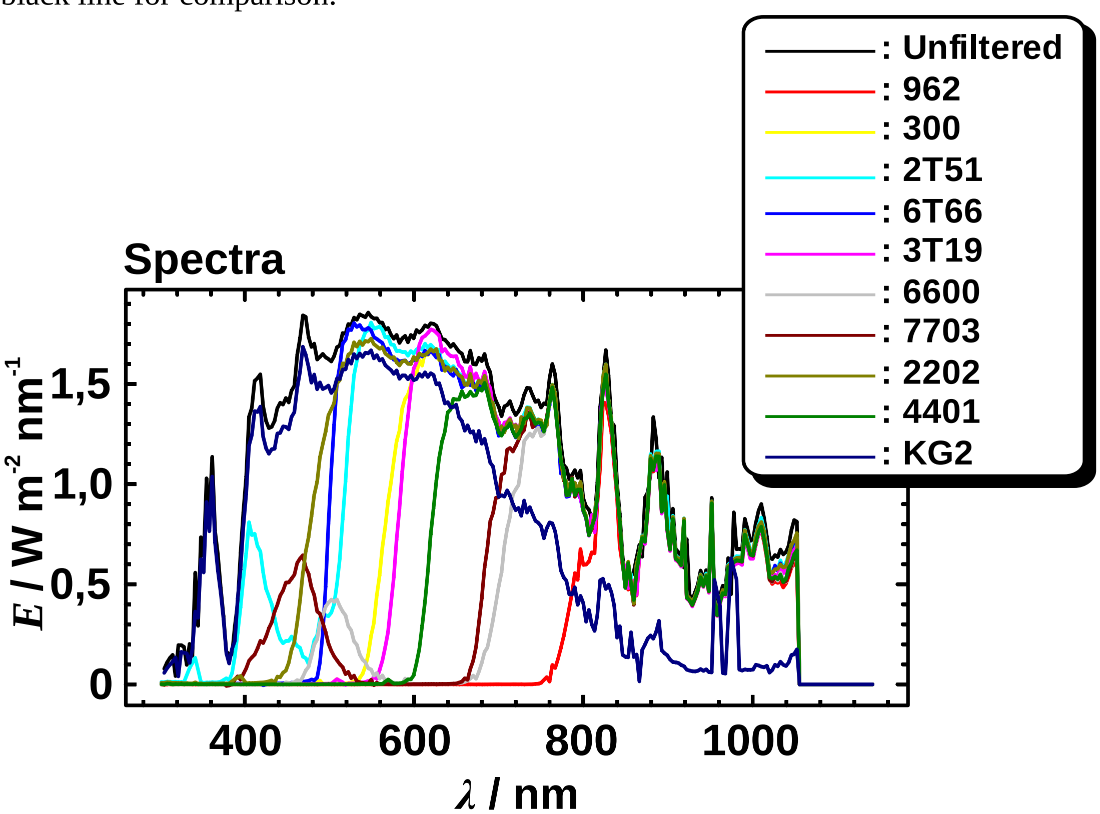


Figure 9: Measured spectra during a polychromatic calibration of the reference solar cell Sample #3 for an ensemble of filters (coloured)

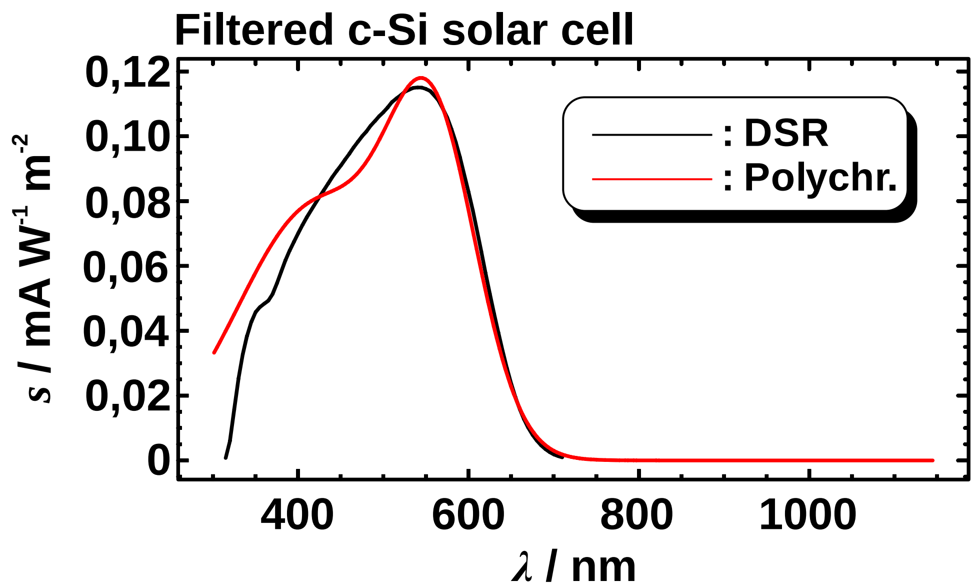


Figure 10: Spectral responsivity: DSR-method at PTB (black) and polychromatic SR-method at LU (red) of the reference solar cell with the ID 132-2012

Table 4: Measured short-circuit currents (I_{SC}) during a polychromatic calibration of the reference solar cell with the ID 132-2012 belonging to Figure 9 for an ensemble of filters. Additionally are the estimated irradiance level (E) given for each filter.

Filter	I_{SC} / mA	E / W m^{-2}
Unfiltered	0,0366	1000
962	-	313
300	0,0093	724
2T51	0,0238	844
6T66	0,0213	829
3T19	0,0073	699
6600	0,0022	483
7703	0,0034	521
2202	0,0238	862
4401	0,0022	618
KG2	0,0324	571

The simulated spectral responsivity disagree between 350 nm and 580 nm to the results of the monochromatic DSR-method. It might be possible, that the spectral information by the polychromatic method is inadequate with the available filters for the determination of the spectral responsivity in this wavelength region. The fitting algorithm works well in the wavelength region above 580 nm.

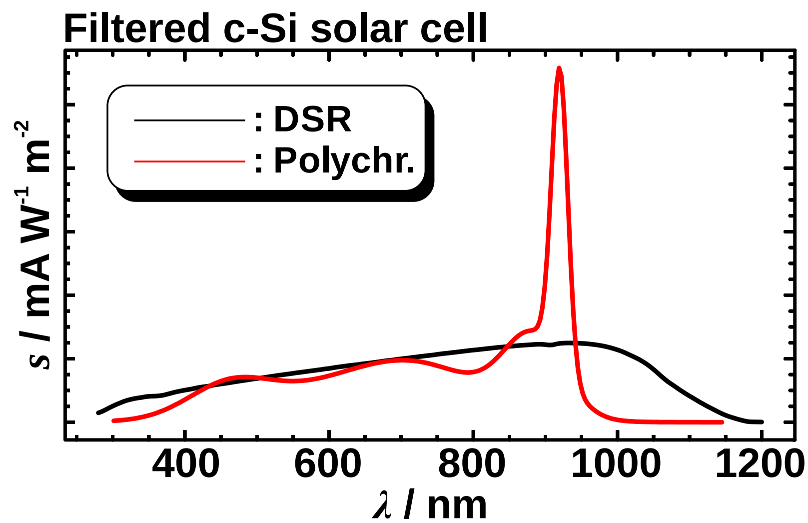


Figure 11: Spectral responsivity: DSR-method at PTB (black) and polychromatic SR-method at LU (red) of the reference solar cell Sample #2

The importance of the spectral information is particularly shown in Figure 11. In Figure 11 are the results of the DSR-method at PTB (black) and the polychromatic SR-method at LU (red) shown. The spectral peaks around λ = 920 nm (shown in Figure 9) causes an extreme enlargement of the simulated spectral responsivity (Figure 11, red) compared to the spectral responsivity determined with the DSR-method. Additionally is the simulated spectral responsivity zero above λ = 1000 nm. Both problems probably causes on insufficient measured spectra with the modified EKO-MS700. The LU plan to improve these measurements with a much better spectroradiometer. With a better spectroradiometer can maybe a better simulated spectral responsivity generated and a short-circuit currents (I_{SC}) subsequently calculated. Another reason can be the unknown correction factors [8], that was applied in Figure 8. These factors are actually not available for the determination and seems to be necessary for good results.
The results of the common solar cell calibration with the PASAN 3b are summarised in Table 5. An uncertainty for the filtered Sample #3 is not shown, because the spectral mismatch can’t be calculated completely due to the limitation of the spectrometer in the high wavelength region.

Table 5: Results of the short-circuit currents under Standard Test Conditions I_{STC} with the PASAN 3b with corresponding expanded measurement uncertainty (k = 2) for the unfiltered reference solar cells

ID	Calibration Date	Reference ID	I_{STC} / mA
Sample #1	28th July 2015	PV13&PV25	141,2 ± 3,9
Sample #2	28th July 2015	PV13&PV25	140,3 ± 3,8
Sample #3	28th July 2015	PV13&PV25	(36,3 ± 1,0)A

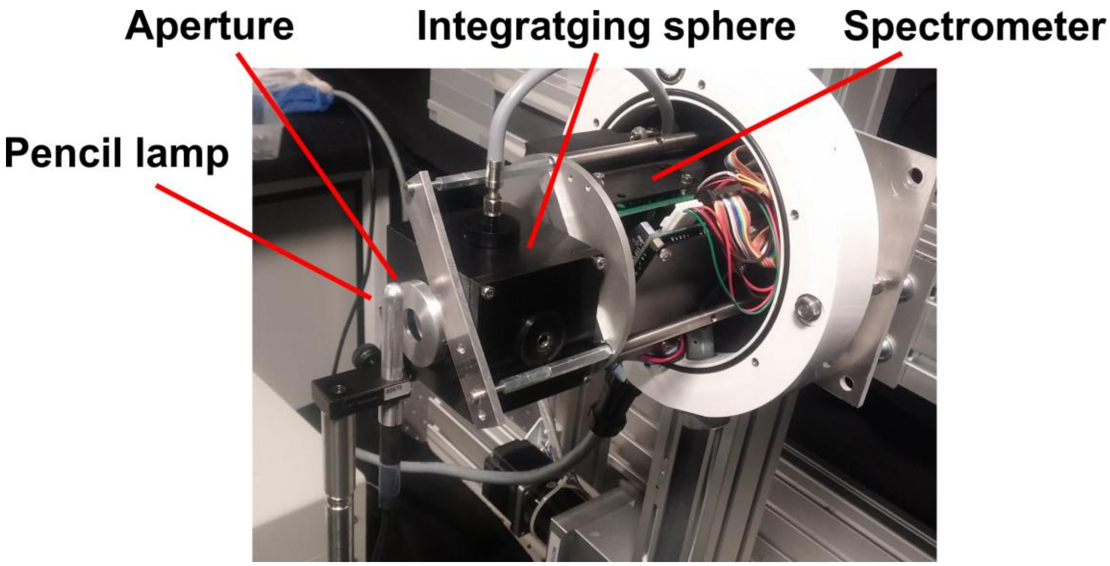


Figure 12: Picture of the modified EKO MS-700

4. Uncertainty analysis of the polychromatic SR-method

The polychromatic spectral responsivity (SR) measurement consist mainly of two parts. The first part are the measurements of the spectra. The spectra are measured with a modified EKO MS-700 (Figure 12). It was calibrated with an Oriel63350_Sn7-1962 standard lamp during the research stay. The second part are the *IV*-measurements with the PASAN 3b solar simulator. This include also the homogeneity of the PASAN 3b polychromatic field and the *IV*-curves.

4.1. Calibration of the modified EKO MS-700

The calibration of the modified EKO MS-700 consist of two parts. The first part is the calibration of the wavelength with a Pencil lamp (Hg(Ar) 6035) and the second part is the calibration with a Quartz Tungsten Halogen lamp (Oriel Model: 63350). Further advanced characterisations of the modified EKO MS-700 like stray light correction and linearity measurements are not performed during the research stay.
The first results of the wavelength calibration showed a wavelength shift of about 3,4 nm. The shift originate from a software problem and is now corrected. The final spectrum of the Pencil lamp (Hg(Ar) 6035) measured with the modified EKO MS-700 is shown in Figure 13.
The estimated uncertainty of the wavelength due to the Difference of the peak positions of the Pencil lamp (Hg(Ar) 6035) between the measured and literature values and the peak positions (Figure 14, $\Delta\lambda \approx \pm 0{,}4$ nm) and the pixel resolution ($\lambda = \pm 1{,}7$ nm) causes a final uncertainty of $u(\lambda) = \pm 2{,}1$ nm ($k = 1$).

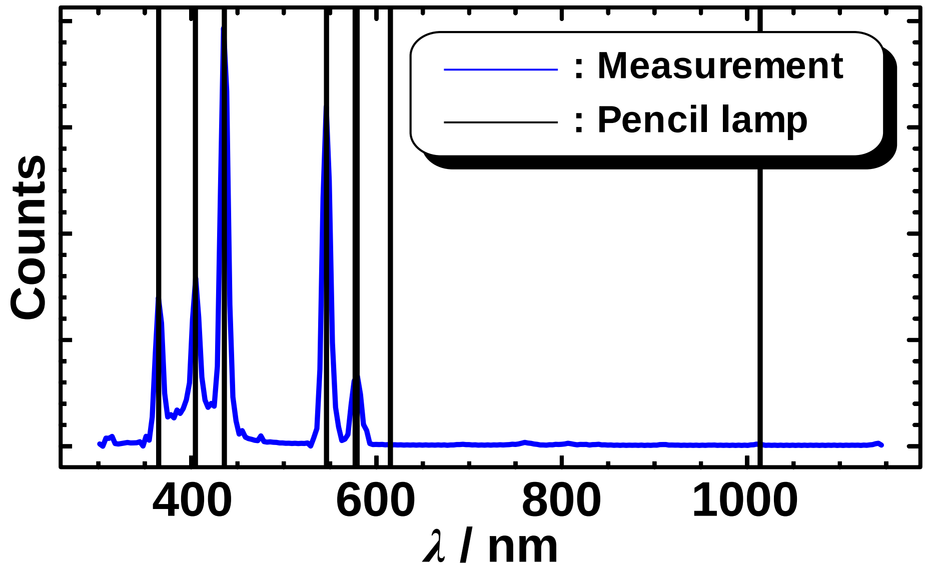


Figure 13: Spectrum of a Pencil lamp (Hg(Ar) 6035, blue) with the modified EKO MS-700 and the spectral lines of the Pencil lamp (Hg(Ar) 6035, black)

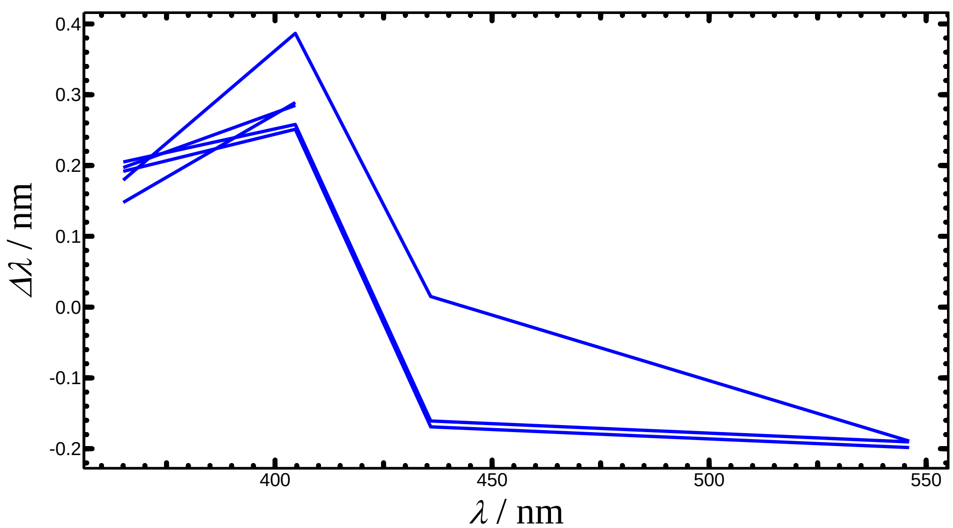


Figure 14: Difference of the measured center wavelengths of the Pencil lamp lines (Hg(Ar) 6035) and corresponding literature values for 12 measurements with different integration times (25 ms - 10000 ms)

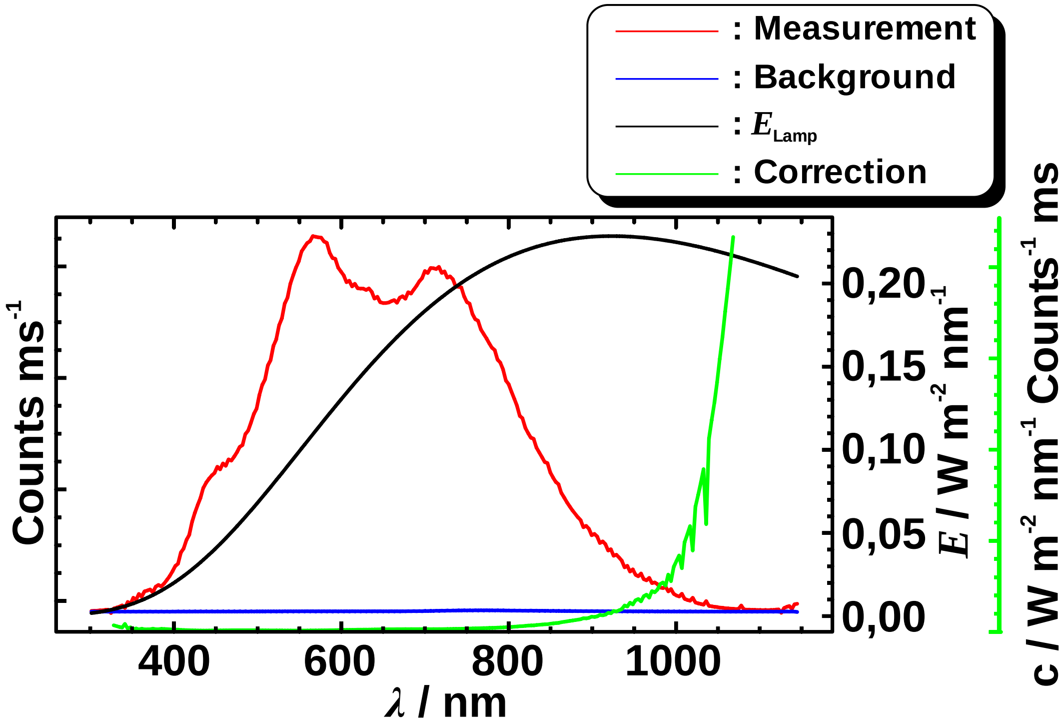


Figure 15: Measuerement (red), background measuremend (blue), specified spectral irradiance of the Quartz Tungsten Halogen lamp (Oriel Model: 63350, black) and the resulting correction function (green)

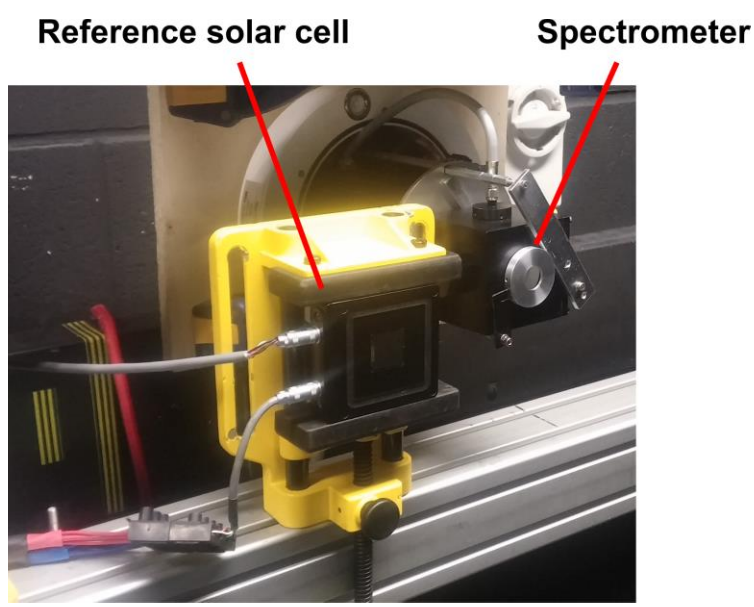


Figure 16: Reference solar cell and modified EKO MS-700 in the measurement plane

During the measurements was a spontaneous carry-over from one pixel to a neighbouring pixels of about 255 counts observed. The reason is not understood yet. The low signal-to-noise ratio above 1080 nm limit also the usability of the spectrometer in the higher wavelength region. Finally the absolute calibration function (correction function (*c*), Figure 15, green) of the spectrometer is used.

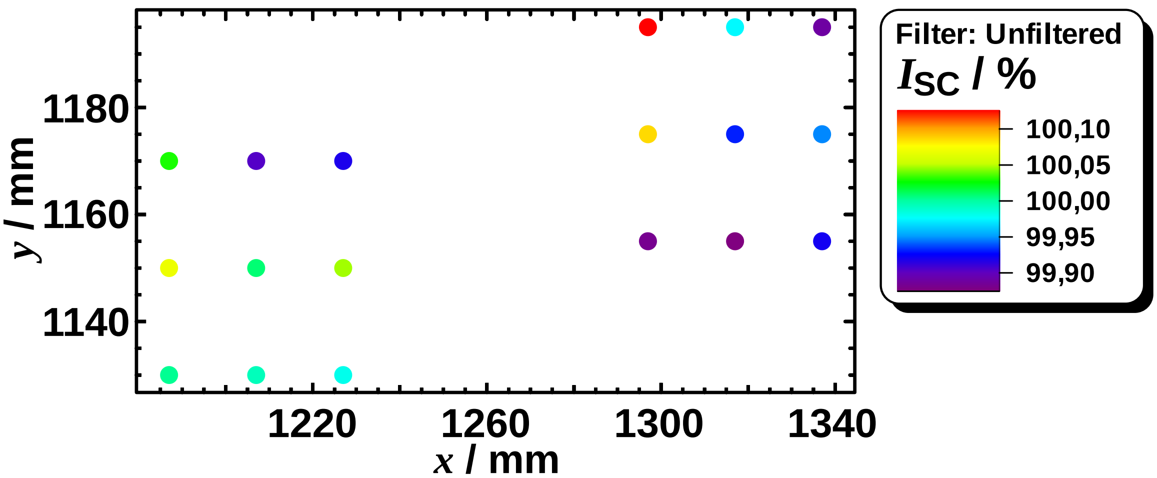


Figure 17: Homogeneity of the unfiltered PASAN 3b in the measurement plane at the positions of the reference solar cell and the modified EKO MS-700

4.2. PASAN 3b: Homogeneity

The measurements of the short circuit currents (I_{SC}) and the spectra of the polychromatic SR-method are simultaneous. Therefore the reference solar cell and the spectrometer are simultaneous measured in the same measurement plane (Figure 16) very close to each other. To estimate an influence due to an inhomogeneity, the homogeneity needs to be measured. The distance to the xenon arc lamps is about 8 m [8]. In this distance should be the homogeneity very well.

The homogeneity is measured with a reference solar given by LU. The area of the solar cell is (2 x 2) cm^2. With this reference was an area around the final solar cell position scanned and also the area of the spectrometer. The results without a filter are shown in Figure 17. The homogeneity is approximately ±0,15 % ($k = 1$). This needs take into account, that the solar cell was manually aligned. Therefore have an additional error due to the angle between the planes of the solar cell and the measurement plane taken into account. The true homogeneity can be better.

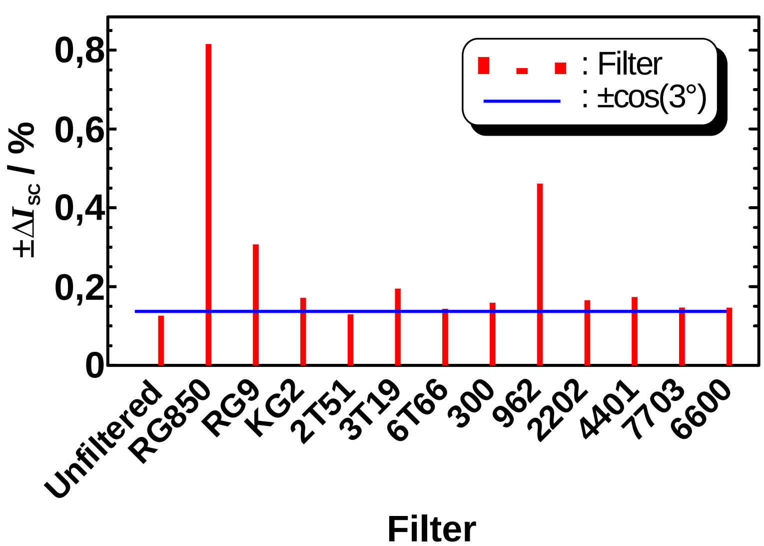


Figure 18: Overview of the homogeneity's of the PASAN 3b with the selected filters.

These measurements were done for all selected filters. The results are summarised in Figure 18. The homogeneity's were mostly approximately due to a misaligned of an angle about 3° (cos(3°) ≈ 0,14). Both results with higher values seems to originate from single measurement points to a misaligned angle. Overall is the homogeneity of the PASAN 3b very well.

4.3. PASAN 3b: Summarize

The calculation of the uncertainty of the spectral responsivity determined by the polychromatic SR-method is not elementary. The uncertainty of the spectral responsivity is with regard to the fitting algorism (section 2.2) und the wavelength limitation of the spectrometer (Figure 15) complicated. Another task are not well kwon correction factors [8]. They seem to be important (Figure 8). Therefore is the uncertainty consideration not complete.
The LU made an estimation for a common solar module calibration [9]. This is in principle similar to solar cell calibration with the PASAN 3b. The estimation include the electrical uncertainty, the temperature uncertainty, the optical uncertainty and the reference device uncertainty. The final uncertainty for the short-circuit currents under Standard Test Conditions (I_{STC}) is $u(I_{STC})$ = ± 2,6 % (k = 2) [9].

5. Summary

A set of three solar cells was investigated at PTB and LU. The research stay was used to transfer knowledge between the researcher and the guest organisation. In this report I presented an overview about the Differential Spectral Responsivity (DSR)-method used at PTB and the polychromatic Spectral Responsivity (SR)-method used at LU.
The DSR-method uses the combination of a modulated (quasi-) monochromatic beam and a white light (bias) source to determine the short-circuit currents under Standard Test Conditions (I_{STC}) and the SR. The polychromatic method uses a PASAN 3b spectrum and a set of broadband filters in combination with the measurements of *IV*-curves to determine the SR and consequently the I_{STC}. The polychromatic method of LU can't be finished, because the spectrometer was not optimised for this task. Therefore the simulations of the SR doesn't works well. A characterisation of selected components of the SR-facility at LU was performed and showed in section 4. The results of the primary calibrations with the facility at PTB and the secondary calibrations with the facility at LU are summarised in Table 6.

Table 6: Results of the short-circuit currents under Standard Test Conditions (I_{STC}) with the DSR-facility at PTB and the PASAN 3b at LU. Also are the En-number (see equation (9)) shown for a conformity of both facilities. In a last step was Sample #1 used as reference solar cell.

ID	PTB $I_{\mathrm{STC,\,PTB}}$ / mA	LU $I_{\mathrm{STC,\,LU}}$ / mA	En-number	LU $I_{\mathrm{STC,\,LU}}$ / mA with reference Sample #1
Sample #1	141,11 ± 0,74	141,2 ± 3,9	0,03	-
Sample #2	140,07 ± 0,74	140,3 ± 3,8	0,06	140,2
Sample #3	35,70 ± 0,20	(36,3 ± 1,0)	(0,59)	(36,2)

The results of both facilities are compared with the En-number (see equation (9)) [10].

$$En_i = \frac{\left|I_{STC,LU} - I_{STC,PTB}\right|}{\sqrt{\left(U(\,I_{STC,LU})\right)^2 + \left(U(I_{STC,PTB})\right)^2}} \qquad (9)$$

The En-numbers are less than 1 and shows a good agreement.

6. Acknowledgement

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7. References

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