UNCERTAINTY ANALYSIS OF A PHOTOMETER CALIBRATION AT THE DSR SETUP OF THE PTB

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ABSTRACT

The uncertainty analysis of a photometer calibration using the Differential Spectral Responsivity method (DSR, [1,2]) will be discussed. The modelling of the measurement procedure includes all relevant contributions in the uncertainty budget of the spectral irradiance responsivity function. The discussion in this report is mainly focused on the correlations between the uncertainties of the responsivity values at different wavelengths and their effect on the integrals for the respective photometric quantities.

Keywords: Spectral responsivity, DSR, Photometer calibration, Uncertainty analysis, Correlations, Monte Carlo

1. INTRODUCTION

At the PTB the DSR-setup (see Fig. 1) was developed to determine the short-circuit current of solar cells including non-linear deviations as well as the responsivity of photometer and radiometer heads under specified level of irradiation.

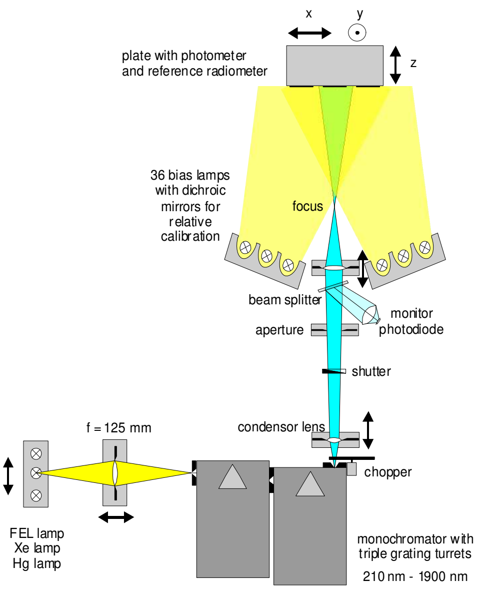

Fig. 1 : Schematic representation of the DSR setup of the PTB

2. EXPERIMENTAL SETUP

A dual-beam optical arrangement is used to measure the DSR-function of the device under test (DUT). A bias beam is produced by up to 36 dichroic halogen lamps and allows to set a series of discrete operating points due to bias irradiation with illuminance levels up to 200 klx.

The chopped monochromatic radiation of a double grating monochromator is used as a second beam, which produces the signal i of the DUT measured with lock-in technique. This signal is compared with the signal i_R of a reference radiometer with known spectral irradiance responsivity s_R at the same position (substitution method). Instability of the irradiance is corrected by the signals i_M and i_{RM} of a monitor photodiode. Thus, the spectral irradiance responsivity s of the photometer is obtained at every wavelength λ:

$$s = s_R \frac{i / i_M}{i_R / i_{RM}} \cdot Corr$$

Provided the two detectors have similar properties, then the substitution method gives results with small correction factors and significantly reduced uncertainties.

Calibrations with the DSR setup are performed at different bias irradiation levels, which allow to identify non-linearities of the responsivity [1]. Non-linearities, however, are not discussed in this document.

The spectral irradiance responsivity function $s(\lambda)$ is the radiometric basis to determine the luminous responsivity

$$s_v = \frac{\int_0^\infty P(\lambda, T_A) \cdot s(\lambda) \, d\lambda}{K_m \cdot \int_0^\infty P(\lambda, T_A) \cdot V(\lambda) \, d\lambda} \qquad (1),$$

where $P(\lambda, T_A)$ is the Planckian distribution at distribution temperature $T_A = 2856$ K that approximates the CIE illuminant A. By the calculating of s_v for different distribution temperatures the mismatch index m is obtained.

3. MODEL OF EVALUATION

For the determination of the spectral responsivity the following model of evaluation is used:

$$s(\lambda) = s_{\mathrm{R}}(\lambda)\,\frac{i(\lambda)/i_{\mathrm{M}}(\lambda)}{i_{\mathrm{R}}(\lambda)/i_{\mathrm{RM}}(\lambda)} \cdot \qquad (2)$$
$$\cdot f_{\mathrm{Unif}}(\lambda)\; f_{\mathrm{WL}}(\lambda)\; f_{\mathrm{BW}}(\lambda)\; f_{\mathrm{Dist}}\; f_{\mathrm{T}}(\lambda)\; f_{\mathrm{Freq}}(\lambda)$$

All quantities - except f_{Dist} - are wavelength-dependent. The symbols mean:

$i(\lambda)$: Photo-current of the irradiated DUT, corrected for dark current.

$i_{\mathrm{M}}(\lambda)$: Photo current of the monitor photodiode, corrected for dark current measured simultaneously to $i(\lambda)$. Up to 50 readings were taken for the four photocurrents at each of the wavelengths. The signals of the devices are divided by the related monitor signal to eliminate the correlations and the statistics of the ratios are used in the evaluation process.

$i_{\mathrm{R}}(\lambda)$, $i_{\mathrm{RM}}(\lambda)$: Measurements with the reference radiometer, similar to those above.

$s_{\mathrm{R}}(\lambda)$: Spectral irradiance responsivity of the reference radiometer, uncertainty stated in certificate.

$f_{\mathrm{Unif}}(\lambda)$: Correction factor for the non-uniformities of photometer $s(x,y,\lambda)$, of reference radiometer $s_{\mathrm{R}}(x,y,\lambda)$ and the irradiation field $E_{\mathrm{real}}(x,y,\lambda)$ from the monochromator :

$$f_{\mathrm{Unif}}(\lambda) = \frac{\int_{A_0} s(x,y,\lambda)\cdot 1\,\mathrm{d}A}{\int_{A_0} s(x,y,\lambda)\cdot E_{\mathrm{real}}(\mathrm{x,y},\lambda)\,\mathrm{d}A} \cdot \frac{\int_{A_0} s_{\mathrm{R}}(x,y,\lambda)\cdot E_{\mathrm{real}}(\mathrm{x,y},\lambda)\,\mathrm{d}A}{\int_{A_0} s_{\mathrm{R}}(x,y,\lambda)\cdot 1\,\mathrm{d}A} \qquad (3)$$

The correction factor is unity for equal sized apertures of reference and uniform DUT or for a highly uniform irradiation field, otherwise the error is corrected and the remaining uncertainty is uncorrelated.

$f_{\mathrm{WL}}(\lambda)$: Correction factor for a wavelength shift, relevant for differently shaped relative spectral responsivity functions of the DUT and the reference. The wavelength correction $\Delta\lambda = \Delta\lambda_1 + \Delta\lambda_2$ has two components, an offset $\Delta\lambda_1 = \pm\,0{,}2$ nm with rectangular probability distribution (RPD), constant for all wavelengths (correlated) and a correction $\Delta\lambda_2 = \pm\,0{,}05$ nm individual for each wavelength due to limited repeatability of the wavelength drive with associated uncertainty normally distributed (uncorrelated).

$$f_{\mathrm{WL}}(\lambda) = \frac{1-\Delta\lambda\cdot i'(\lambda)/i(\lambda)}{1-\Delta\lambda\cdot i_{\mathrm{R}}'(\lambda)/i_{\mathrm{R}}(\lambda)}$$

$f_{\mathrm{BW}}(\lambda)$: Correction factor for the monochromator bandwidth $\Delta\lambda_{1/2} = 6$ nm $\pm$ 2 nm considering a triangle slit function.

$$f_{\mathrm{BW}}(\lambda) = \frac{1-\Delta\lambda_{1/2}^{\;2}\cdot\frac{1}{12}\cdot i''(\lambda)\big/ i(\lambda)}{1-\Delta\lambda_{1/2}^{\;2}\cdot\frac{1}{12}\cdot i_{\mathrm{R}}''(\lambda)\big/ i_{\mathrm{R}}(\lambda)}$$

It depends on differences between the 2$^{\mathrm{nd}}$ deviation of the responsivity functions of DUT and reference. The large variation (2 nm) includes a slit function being not perfect triangle-shaped and the low order approximation for the correction.

$f_{\mathrm{Dist}}(\lambda)$: corrects for different effective distances of DUT and reference to the focus behind the monochromator.

$$f_{\mathrm{Dist}} \approx 1 + 2\cdot\Delta r/r_0 \cdot$$

$f_{\mathrm{Temp}}(\lambda)$: Correction for wavelength dependent temperature coefficients of DUT and reference.

$$f_{\mathrm{WL}}(\lambda) = \frac{1-\Delta T\cdot\frac{\partial i(\lambda)}{\partial T}\Big/ i(\lambda)}{1-\Delta T\cdot\frac{\partial i_{\mathrm{R}}(\lambda)}{\partial T}\Big/ i_{\mathrm{R}}(\lambda)}\;.$$

$\Delta T = \pm\,0{,}1$ K is the difference to the nominal temperature. If the photometer has a build-in temperature control, it is difficult to measure its temperature coefficient $\partial i/\partial T$ directly.

$f_{\mathrm{Freq}}(\lambda)$: Correction factor for a frequency dependence of the responsivity functions due to the modulated light for the lock-in technique. It was checked that it is negligible.

It was found to be extremly complex to calculate the uncertainty of the photometric responsivity according to formula (1) using the conventional GUM:

- Formula (1) uses 236 spectral responsivities of formula (2) (from 360 nm to 830 nm with an increment of 2 nm).
- Each value of formula (2) uses 11 uncertainty components and some of them even create correlations between the 236 spectral responsivities, e.g. $f_{\mathrm{WL}}(\lambda)$.

A more practical approach is the use of the Monte-Carlo-Method [3], with the advantage that it considers correlations automatically (see Fig. 2).

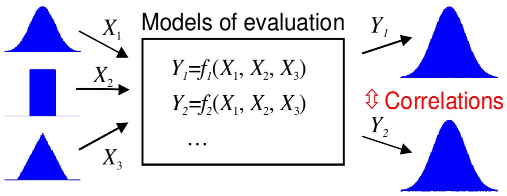

Fig. 2 : Principle of the Monte-Carlo-Method. Step 1: Create a complete set of random input variables X_i with appropriate distributions. Step 2: Use this set to calculate all results Y_j according to the models of evaluation. Step 3: Save all important input variables and results. Steps 1 to 3 are repeated often. Use the saved results to calculate the standard deviations, the distributions functions and correlations between the input or output quantities.

4. RESULTS

The directly calculated spectral responsivity and its associated uncertainty as a result of the Monte-Carlo-Simulation are shown in Fig. 3.

The correlation matrix of the relative spectral responsivities is drawn in Fig. 4 showing strong positive correlations between responsivities on the same edge of the spectral responsivity function and strong negative correlations between responsivities on different edges. Only those values, where the signal to noise ratio of the photometer was not large enough are uncorrelated. The correlation matrix of the absolute spectral responsivities is shown in Fig. 5. Because of additional uncertainty components, the correlations are smaller than in Fig. 4.

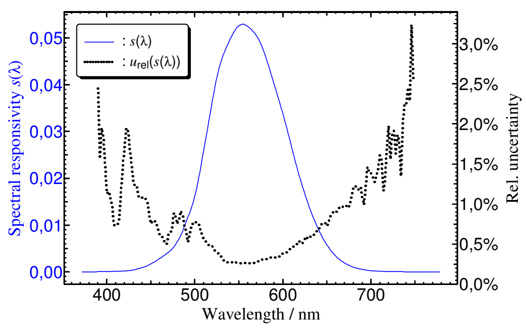

Fig. 3 : Wavelength dependence of the spectral responsivity function and the associated uncertainty.

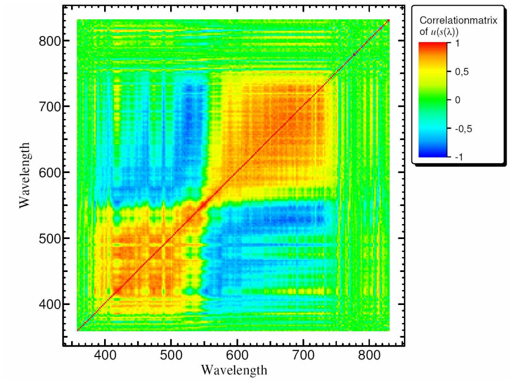

Fig. 4 : Correlation matrix of the relative spectral responsivities.

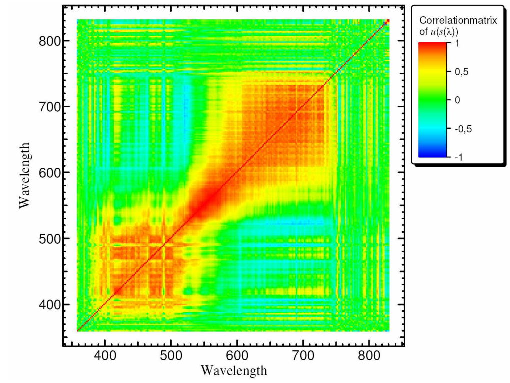

Fig. 5 : Correlation matrix of the absolute spectral responsivities. The structure of the diagram is washed out due to more contributions.

In order to analyse the reason of the correlations, the uncertainty of the wavelength offset was set to zero. In this case only the correlations due to the bandwidth uncertainties remain (see Fig. 6a). If this is set to zero, too, even that pattern disappears (see Fig. 6b). This assumption can be made, if a tuneable laser is used for the calibration. But in that case other uncertainties e.g. because of interferences must be taken into account.

Fig. 7 shows, that there is a high correlation between the wavelength offset and the mismatch index m, independent of all other quantities. Therefore, the value of the mismatch index can be used to test the wavelength calibration, if it is determined by another independent method. The resulting distribution function of the mismatch index is a combination of a normal and a rectangular distribution.

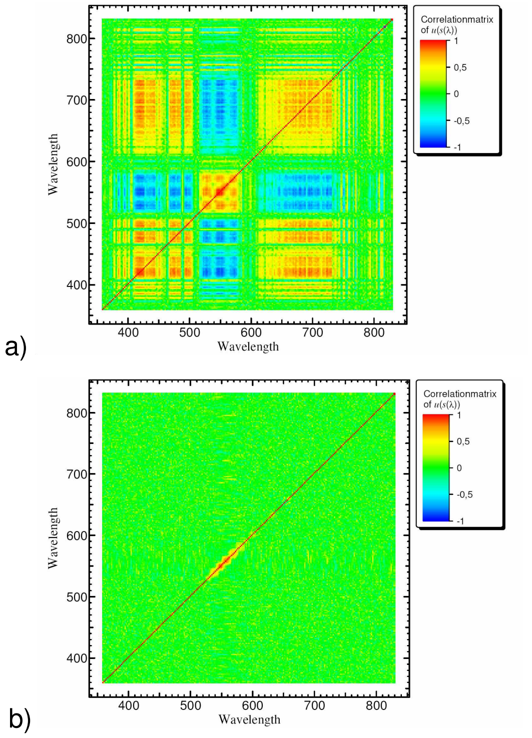

Fig. 6 : Correlation matrix of the relative spectral responsivities, a) if the wavelength offset uncertainty is set to zero and b) if the bandwidth error is zeroed, additionally.

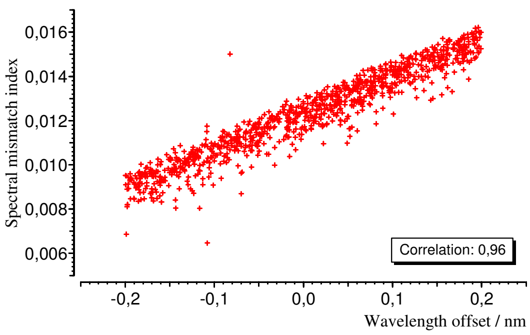

Fig. 7 : 1000 draws of a Monte-Carlo-Simulation of the mismatch index versus the wavelength, which shows the high correlation between these two quantities.

In addition to the Monte-Carlo-Simulation (dashed curve) the uncertainty of the spectral responsivity was calculated using the methods following the conventional GUM approach (solid curves). The results are identical within the limits of a finite number of simulations (see Fig. 8).

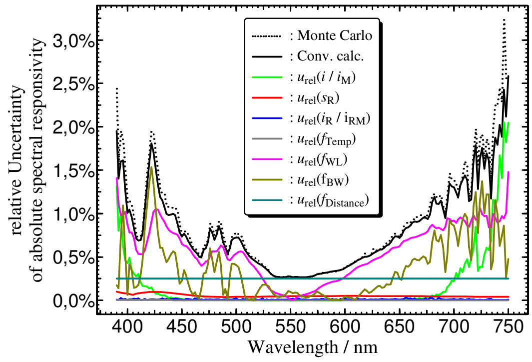

Fig. 8 : Uncertainties of the spectral responsivities, calculated by a Monte-Carlo Simulation and by a conventional approach.

5. CONCLUSION

The uncertainties of the spectral responsivity function were calculated using the Monte-Carlo-Method. Within the limits of the simulation they were found to be identical with those calculated by the conventional GUM approach. But in addition, the Monte-Carlo-Simulation allows the determination of the correlations between the different spectral responsivities and the calculation of the uncertainty of the photometric responsivity (weighted integral) and the mismatch index under consideration of the correlations without additional effort. In this analysis the correlations are mainly originated by a constant wavelength offset.

The Monte-Carlo-Method has proved as a powerful method to calculate the uncertainty even if complex models of evaluation must be used and in the presence of correlations.

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