SPECTRAL MISMATCH CORRECTION FACTOR ESTIMATION FOR WHITE LED SPECTRA BASED ON THE PHOTOMETER'S f_1' VALUE

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Abstract

The spectral matching of photometers is important for photometric measurements. However, there is no general estimation for the spectral mismatch correction factor [1] for the measurement of white LEDs known in the literature until now.
The authors will give a general estimation of the range of possible spectral mismatch correction factors for white LED measurements as a function of the quality of the spectral mismatch of the photometer. For this purpose, a database of 120 different photometers with the general $V(\lambda)$ match quality index f_1' values in the range of 0.6% up to 9.0% and 300 white LED spectra (phosphor type as well as RGB type LEDs based on measurements as well as simulations) was used to calculate the spectral mismatch correction factors. From all data a general observation is derived that the minimum and maximum spectral mismatch correction can be estimated based on the f_1' value of the photometers.

Keywords: photometry, spectral mismatch correction, characterisation, CIE 023

1 Introduction

The spectral matching of photometers is a key property of photometers and can be described by the general $V(\lambda)$ match quality index f_1' derived from the spectral responsivity [1]. The calibration of photometers is usually done for CIE Standard Illuminant A. A non-perfect match, however, makes a spectral mismatch correction for spectral power distributions different from CIE Standard Illuminant A necessary. This can be done directly using the spectral power distribution of the light source to be measured and the spectral responsivity of the photometer and will be explained together with other basic definitions in section 2. In section 3, the database for the investigations is described in detail. The result of the evaluations is shown in section 4 and summarized in section 5.

2 Basic definitions

In the following, the basic definitions from [1] are summarized to specify the calculations for the following sections.

2.1 Spectral mismatch correction factor

Based on the relative spectral responsivity of the photometer $s_{\mathrm{rel}}(\lambda)$ and the relative spectral power distribution of the light source Z $S_{\mathrm{Z}}(\lambda)$, the relative luminous responsivity with respect to light source Z with respect to CIE Standard Illuminant A ($S_{\mathrm{A}}(\lambda)$) is then given by [1]:

$$a^{*}\left(S_{\mathrm{Z}}(\lambda)\right)=\frac{s_{\mathrm{Z}}}{s_{\mathrm{A}}}=\frac{\int_{\lambda_{\min}}^{\lambda_{\max}} S_{\mathrm{Z}}(\lambda)\cdot s_{\mathrm{rel}}(\lambda)\,\mathrm{d}\lambda}{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} S_{\mathrm{Z}}(\lambda)\cdot V(\lambda)\,\mathrm{d}\lambda} \Bigg/ \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} S_{\mathrm{A}}(\lambda)\cdot s_{\mathrm{rel}}(\lambda)\,\mathrm{d}\lambda}{\int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} S_{\mathrm{A}}(\lambda)\cdot V(\lambda)\,\mathrm{d}\lambda} \quad (1)$$

where

s_{Z} is the luminous responsivity of the photometer using light source Z; and

s_{A} is the luminous responsivity of the photometer using CIE Standard Illuminant A.

The lower and upper integration limits ($\lambda_{min}, \lambda_{max}$) should refer to the entire wavelength range where $s_{rel}(\lambda)$ has non-zero values. The reciprocal of $a^*(S_Z(\lambda))$ is called the spectral mismatch correction factor $F^*(S_Z(\lambda)) = \left(a^*(S_Z(\lambda))\right)^{-1}$ (sometimes also abbreviated to *SMCF*).

2.2 Characteristic value *f*1'

Using the (relative) spectral responsivity $s_{rel}(\lambda)$ a normalized spectral responsivity function is defined as follows [1]:

$$s_{rel}^*(\lambda) = s_{rel}(\lambda) \cdot \frac{\int_{380\,nm}^{780\,nm} S_A(\lambda) \cdot V(\lambda)\, d\lambda}{\int_{380\,nm}^{780\,nm} S_A(\lambda) \cdot s_{rel}(\lambda)\, d\lambda} \tag{2}$$

where $S_A(\lambda)$ is the spectral distribution function of the CIE Standard Illuminant A, which, in principle, is used for the calibration of a photometer. The index f_1' is then defined by:

$$f_1' = \frac{\int_{380\,nm}^{780\,nm} \left| s_{rel}^*(\lambda) - V(\lambda) \right| d\lambda}{\int_{380\,nm}^{780\,nm} V(\lambda)\, d\lambda}. \tag{3}$$

The index f_1' is only a characteristic value and it is, in general, not possible to use this value as a correction factor. Furthermore, this value did not limit the measurement error due to the non-perfect spectral matching and cannot be handled as a measurement uncertainty.

However, there is a special interest whether this characteristic value can give some advice about the possible spectral mismatch correction factor for the application of measuring white light based on phosphor type or RGB type LEDs.

3 Database

To check the dependence of the spectral mismatch correction factor from the spectral mismatch index, a collection of (relative) spectral responsivity functions of a wide range of photometers was used and, furthermore, a collection of spectral power distributions of phosphor and RGB type white LEDs.

3.1 Spectral responsivity of photometers

For the calculations a database of 120 photometer measurements is used. There were very different sources of the measurements, and most of them were distributed without measurement uncertainty. Therefore, an analysis of the influence of the measurement uncertainty of the spectral responsivity measurements to the estimations carried out in this contribution was not performed.

Figure 1 shows the data of an example photometer. The relative spectral responsivity of the photometer is shown together with the $V(\lambda)$ function. Furthermore, the spectral mismatch correction factor is calculated for monochromatic light and simulated LED spectral with 20 nm bandwidth.

Figure 2 shows an overview of the distribution of the f_1' values in the database.

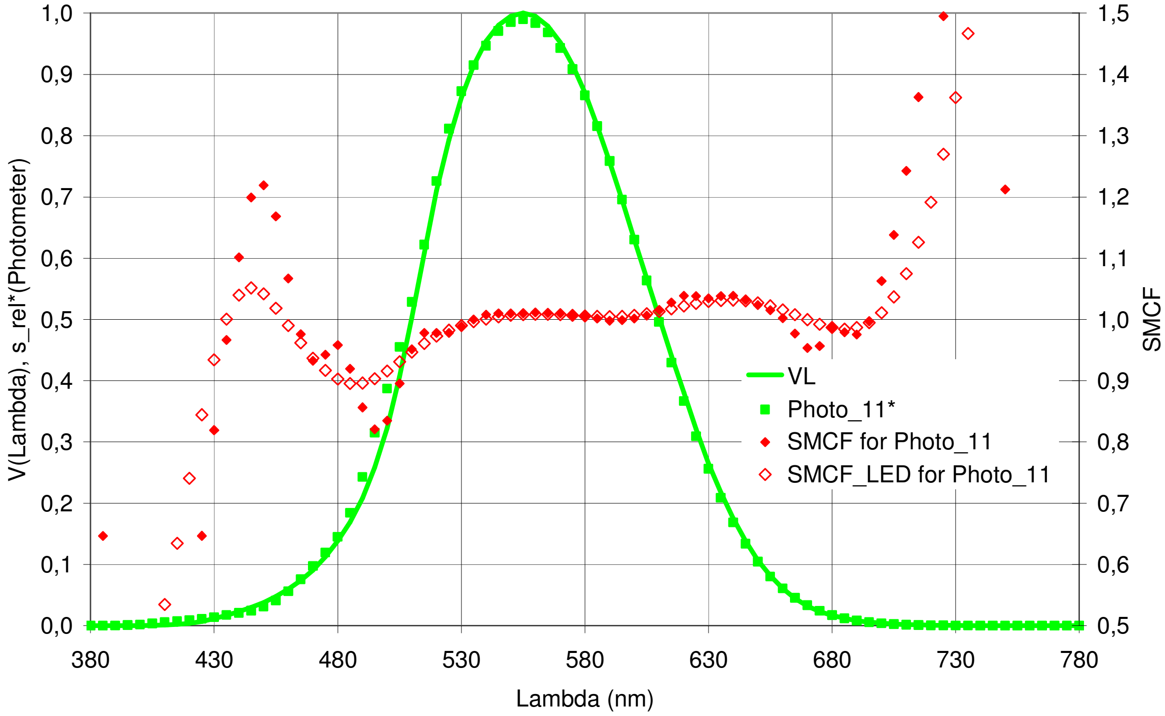

Figure 1 – Spectral responsivity of a photometer and spectral mismatch correction factors for narrowband light (monochromatic) and coloured LEDs (20 nm bandwidth)

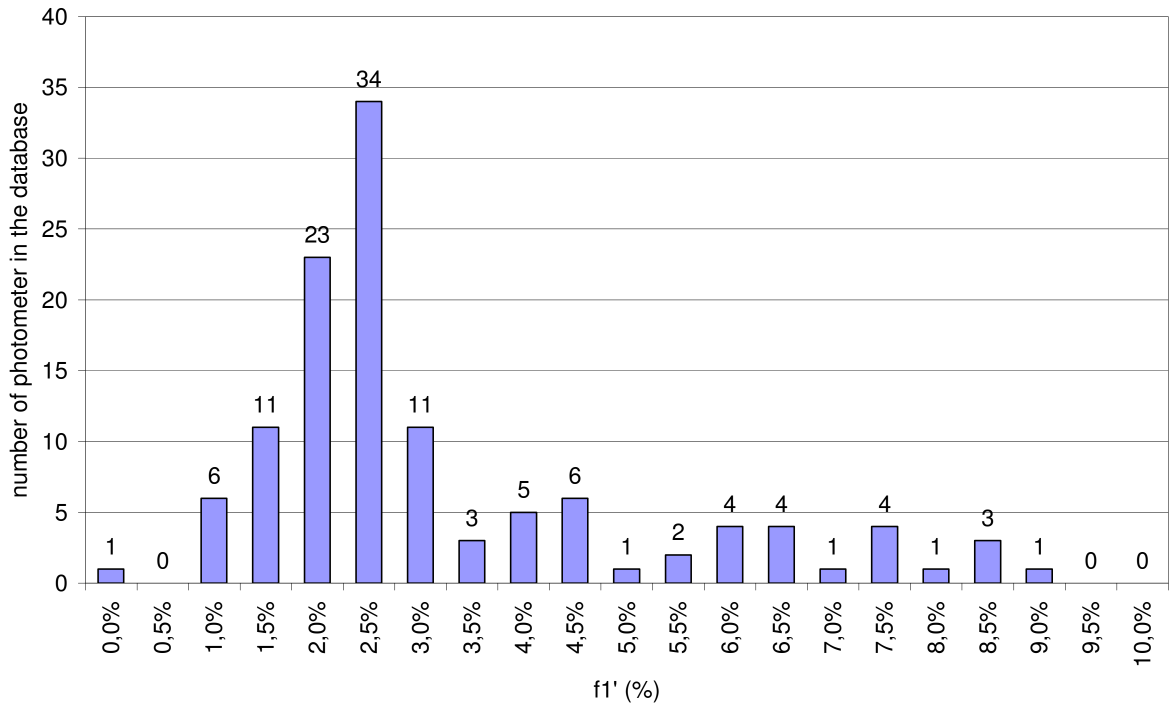

Figure 2 – Number of photometers in the database depending on the f_1' value

3.2 Spectral power distributions of white LEDs

For white LEDs different spectral power distributions from measurements and simulations are used. The following figure shows some examples.

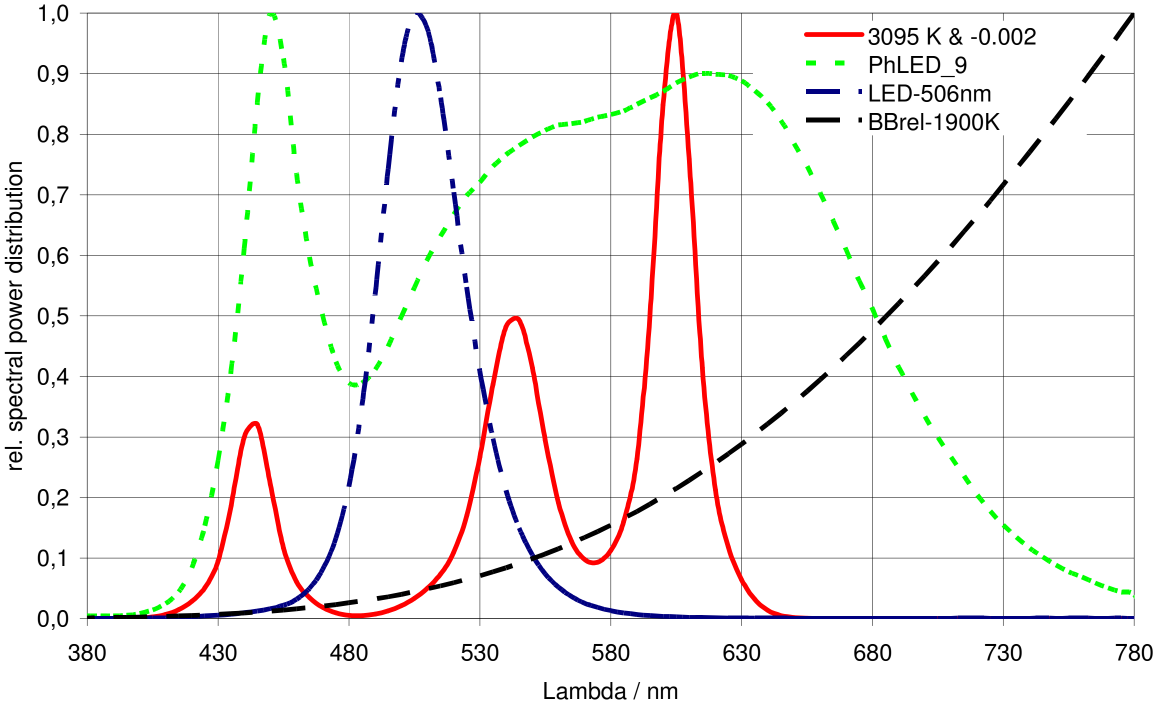

Figure 3 – Relative spectral power distributions for different kinds of light sources from the database

3.2.1 White LEDs

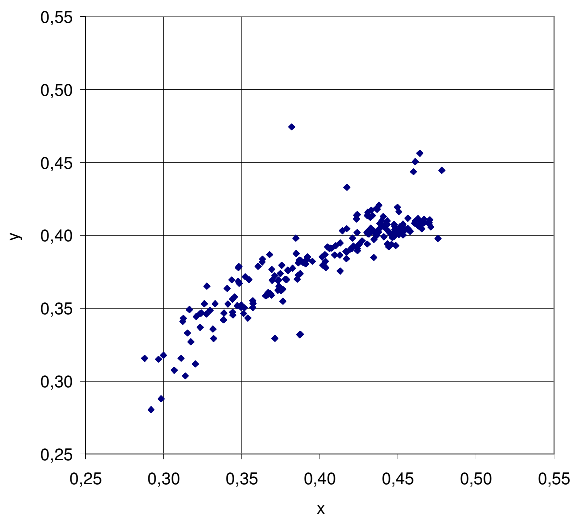

Figure 4 – Distribution of the tristimulus values of phosphor type white LEDs in the database

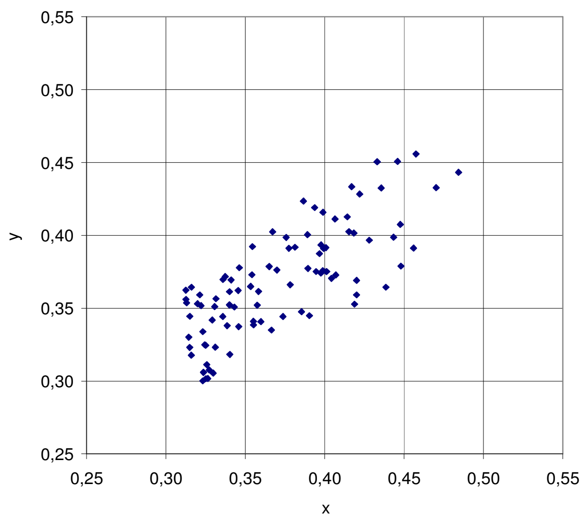

Figure 5 – Distribution of the tristimulus values of RGB type white LEDs in the database

From Figure 4 and Figure 5 the tristimulus values from the spectral power distributions from the database can be seen. Figure 4 shows the distribution from the phosphor type LEDs covering a correlated colour temperature range from 2500 K to 7000 K, and Figure 5 shows the distribution from the RGB type LEDs covering a correlated colour temperature range from 2500 K to 6500 K.

3.2.2 Other light sources

Furthermore, the simulation was carried out for coloured LEDs of various types (a large number of LEDs with the peak wavelength in the range of 400-700 nm were used) and simulated Planckian radiators in the range of 1500K to 6500K.

4 Evaluation

For the evaluation, the calculation was processed as follows:

- All photometers from the database are numbered with $s_{i,\mathrm{rel}}(\lambda)$.
- The different spectral power distributions are numbered inside their category (e.g. RGB type white LEDs, phosphor type white LEDs, ...) with $S_j(\lambda)$.
- According to (1), the spectral mismatch correction factor for all combinations of photometers and light sources in the category is calculated and named as $F^*(i,j)$.
- For the presentation of the data in the following figures, only the minimum and maximum values for all light sources depending on the photometers are shown $F^*_{\min}(i) = \min_j F^*(i,j)$ (red marks) and $F^*_{\max}(i) = \max_j F^*(i,j)$ (green marks).
- For all $F^*_{\min}$ and $F^*_{\max}$ values, the ratios $Q_{\min}(i) = (F^*_{\min}(i) - 1) / f_1'(i)$ and $Q_{\max}(i) = (F^*_{\max}(i) - 1) / f_1'(i)$ are calculated. Using a histogram evaluation the 95% quantile is calculated for the $Q_{\min}(i)$ and $Q_{\max}(i)$ values (designated as $Q_{\min,\alpha}$ and $Q_{\max,\alpha}$). This means 95% of all photometers can be described using these numbers. With further simplification we summarize $Q_{\min,\alpha}$ and $Q_{\max,\alpha}$ to $Q_\alpha = \max(|Q_{\min,\alpha}|, |Q_{\max,\alpha}|)$. This means, the value Q_α can be used as expanded uncertainty of a normal distributed function.
- Using Q_α the following statement is possible: $|F^* - 1| < Q_\alpha \cdot f_1'$ (for the given category of light sources).

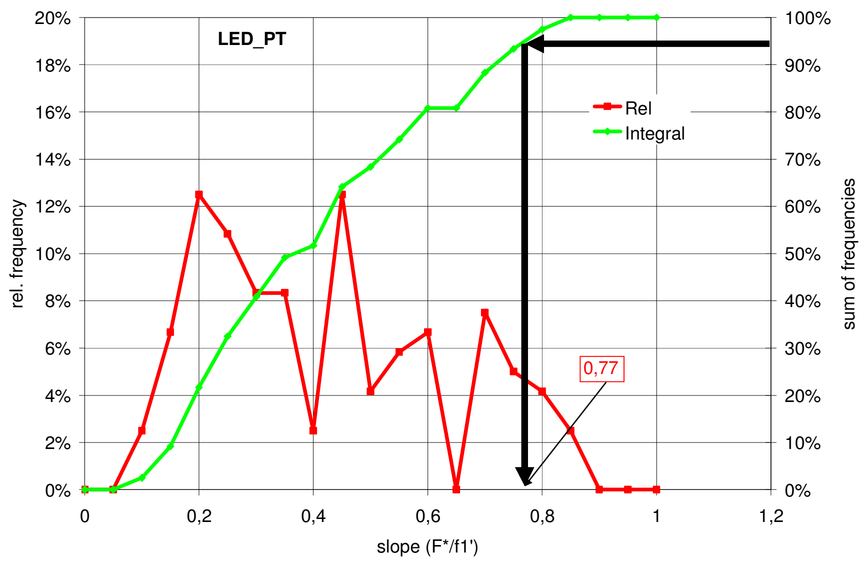

Figure 6 – Calculation of Q_α using the quantile technique for the phosphor type LEDs

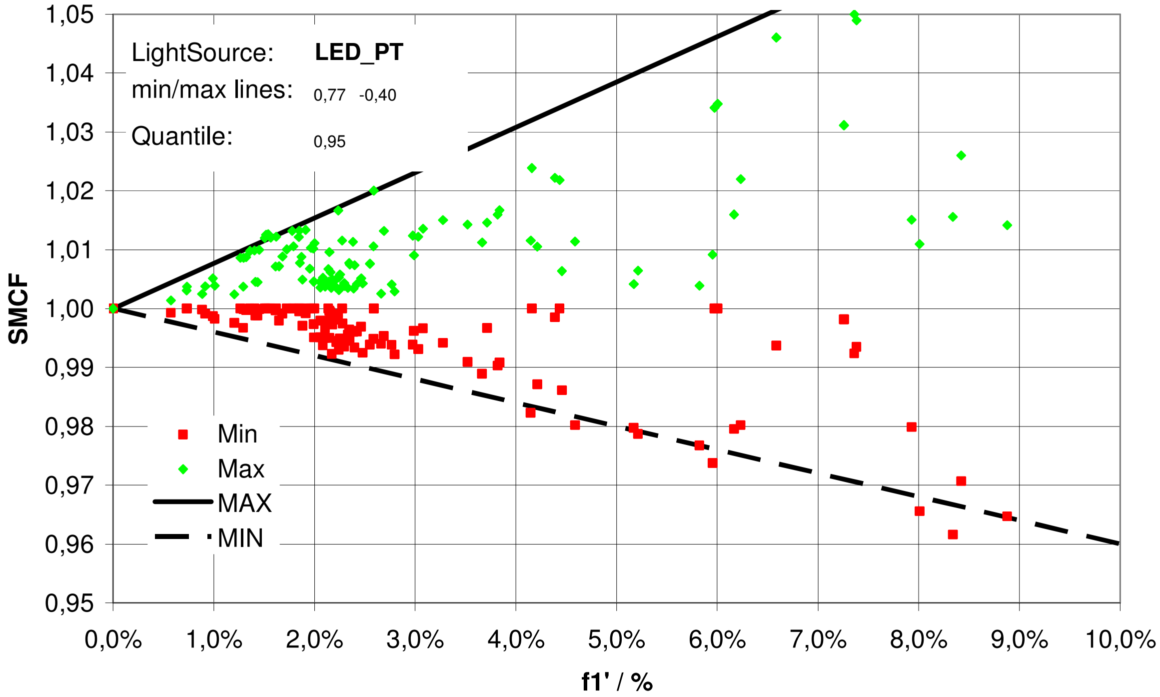

Figure 7 – Minimal and maximal spectral mismatch correction factor for phosphor type white LEDs depending on the f_1' value of the photometers used

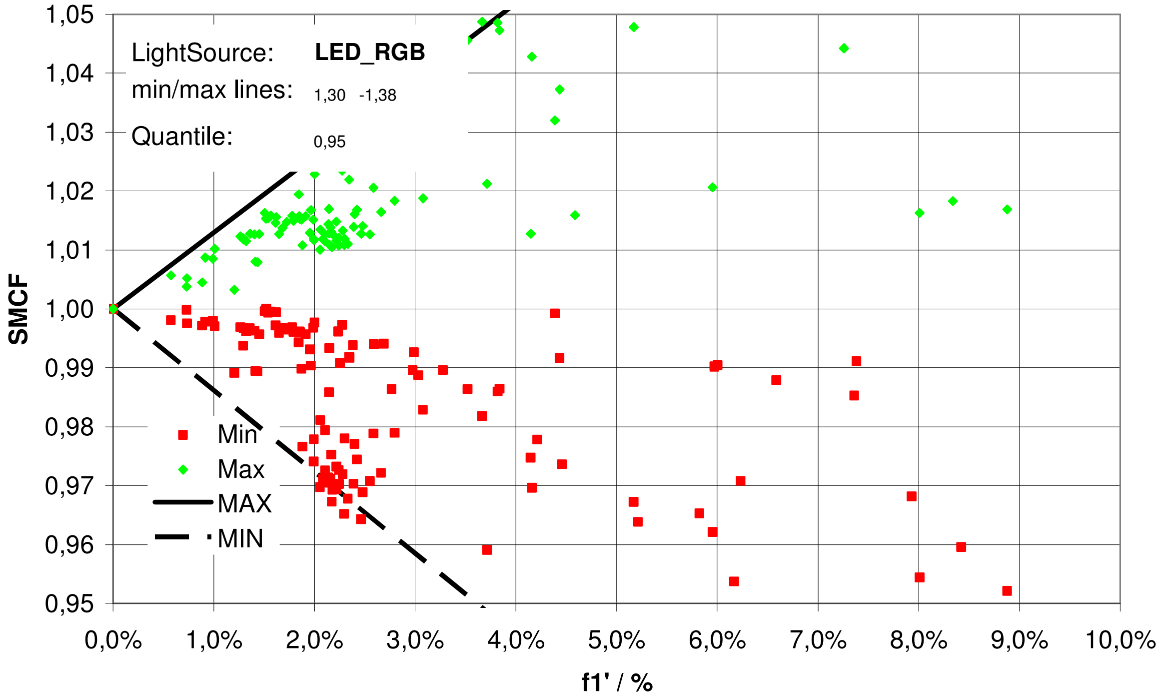

Figure 8 – Minimal and maximal spectral mismatch correction factor for RGB-type white LEDs depending on the f_1' value of the photometers used

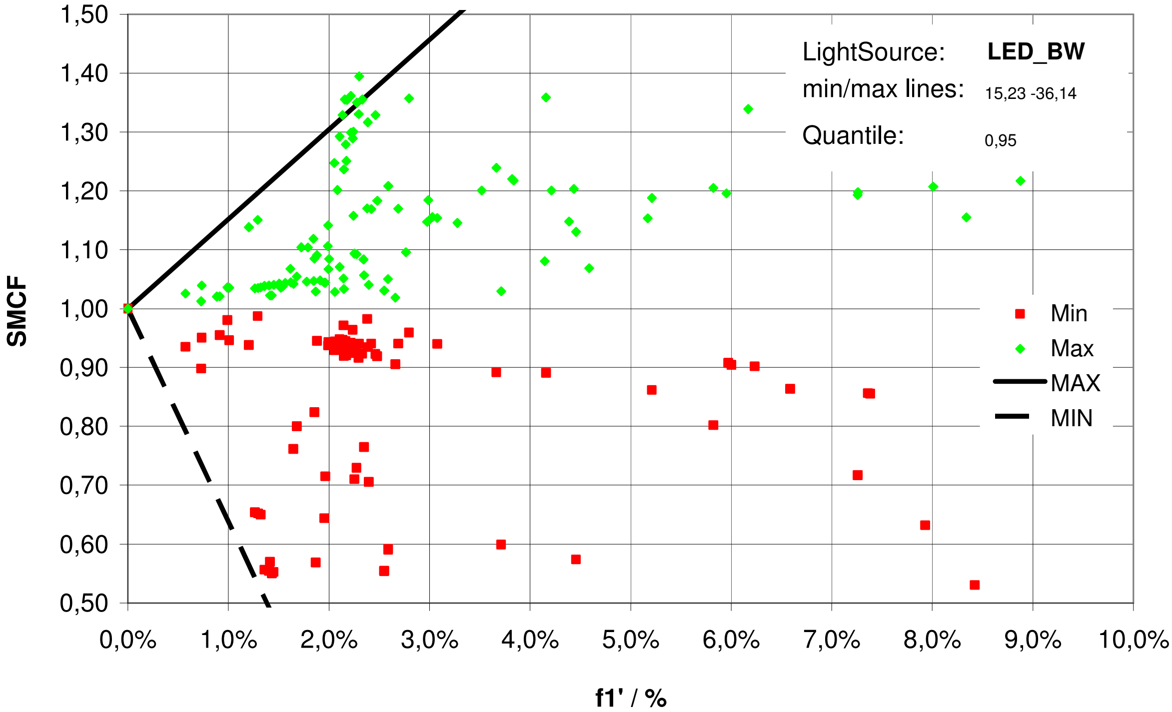

Figure 9 – Minimal and maximal spectral mismatch correction factor for coloured LEDs depending on the f_1' value of the photometers used (*Attention: Different scaling compared to Figure 7 and Figure 8)*

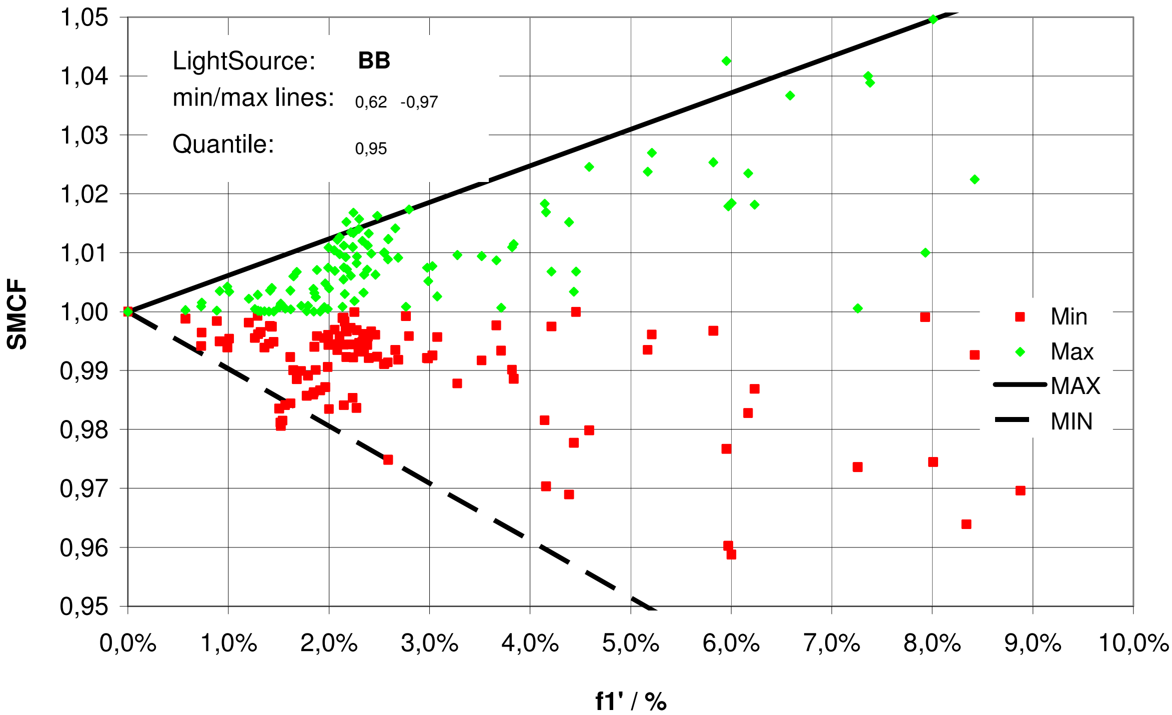

Figure 10 – Minimal and maximal spectral mismatch correction factor for Planckian radiation depending on the f_1' value of the photometers used

Table 1 – Summary of the results for all light source categories

Category	$Q_{\min,\alpha}$	$Q_{\max,\alpha}$	Q_{α} (rounded)	Figure
Phosphor type	-0.40	0.77	**0.8**	Figure 7
RGB type	-1.38	1.30	**1.4**	Figure 8
Coloured LED	*-36*	*15*	***36***	Figure 9
Planckian radiation	-0.97	0.62	**1.0**	Figure 10

- For the coloured LEDs this approach is not applicable. This means, there is no useful estimation of the spectral mismatch correction factor based on f_1' available. (See also Figure 9)
- For Planckian radiation, the method is also available and results in the simple statement that the spectral mismatch correction factor ($|F^* - 1|$) is smaller than the f_1' value.

5 Summary

The spectral mismatch correction factor F^* for white LEDs is estimated (from the database used by the authors) to lie, with 95% probability, in the range defined by

$|F^* - 1| < 0.8 \cdot f_1'$	for phosphor type white LEDs
$|F^* - 1| < 1.4 \cdot f_1'$	for RGB type white LEDs
$|F^* - 1| < 1.0 \cdot f_1'$	for black body radiation in the range of 1500K to 6500K

These estimations of the range of possible spectral mismatch correction factors can also be used for the estimation of the contribution to the measurement uncertainty.
As an example, the spectral mismatch of a photometer with a quality index f_1'of 6% will contribute about 4.2% (used as standard uncertainty of a normal distributed quantity) to the combined uncertainty for the measurement of a white LED of RGB type. This uncertainty could only be reduced if the spectrum of the source and the spectral response of the photometer are known.

References

[1] CIE 2012. CIE Draft Standard DS 023/E:2012. Characterization of the Performance of Illuminance Meters and Luminance Meters, Vienna, CIE, 2012.