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Published in:
Proceedings of CIE 2016 "Lighting Quality and Energy Efficiency"

Publication date:
2016

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Thorseth, A., Lindén, J., & Dam-Hansen, C. (2016). A comparison of goniophotometric measurement facilities. In Proceedings of CIE 2016 "Lighting Quality and Energy Efficiency" (pp. 547-554). CIE - International Commission on Illumination.

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A COMPARISON OF GONIOPHOTOMETRIC MEASUREMENT FACILITIES

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Abstract

In this paper, we present the preliminary results of a comparison between widely different goniophotometric and goniospectroradiometric measurement facilities. The objective of the comparison is to increase consistency and clarify the capabilities among Danish test laboratories. The study will seek to find the degree of equivalence between the various facilities and methods. The collected data is compared by using a three-way variation of principal component analysis, which is well suited for modelling large sets of correlated data. This method drastically decreases the number of numerical values needed to represent the data. The model shows good agreement with data, while also highlighting the differences between the measurements. We conclude that the method could be useful for comparing large sets of goniophotometric data.

Keywords: e.g. Goniophotometry, Intensity distributions, principal component analysis,

1 Introduction

The interest in angle resolved characterization of light sources is currently increasing. This is caused by an increased use of lighting simulations for illuminance specifications, glare evaluations, visualisations, etc. Furthermore, the many new specialized LED luminaires and lamps increase the need for goniophotometric and goniospectroradiometric measurements. This calls for test laboratories to ensure the accuracy and reproducibility of their measurements and correctly estimate and state uncertainties on the measured parameters as specified in the CIE test standard for LED lamps and luminaires (CIE, 2015). This standard specifies the conditions and requirements for goniophotometric measurements using a conventional goniophotometer system, i.e. a mirror based far field goniophotometer where the lamp/luminaire is only rotated around the gravitational axis. It states that other types of goniophotometers may be used only if they are demonstrated to produce equivalent results. However, many different types of goniophotometer and goniospectroradiometer facilities exist and they differ e.g. by the way the artefact or device under test (DUT) is positioned and moved during the measurement of the light intensity distribution (LID). Therefore, one of the purposes of this study is to test if this equivalence can be shown for some of the various types of goniophotometer facilities. One effective tool towards showing this equivalency is to compare measurements from different laboratories and if possible different test methods. From a comparison of results of the same parameters measured from the same or similar devices, laboratories can estimate their measurement capabilities and uncertainties. Some laboratory comparisons are formal and can be used directly, for instance for proficiency testing needed in accreditation of a laboratory. These comparisons have rigid procedures such as the ones described by CIPM (CIPM, 2014). An example of such a comparison is the IC2013 (Ohno et al., 2014), that was designed to investigate the reliability and reproducibility of the new test standard CIE S025 (CIE, 2015). The comparison described in this paper is more informal, enabling a more flexible and collaborative process but missing some of the benefits of a formal comparison.

The output of a goniophotometric measurement is a light intensity distribution. This multivalued two-dimensional data set presents challenges when comparing different measured distributions. One approach is to compare distributions two-by-two as suggested by (Gassmann et al., 2015), however, in this method a reference LID has to be selected for the comparison, which was not readily available in this pilot study. Accordingly, we have tested a way to compare different measurements against each other using a statistical method, based on principal component analysis (PCA). PCA is used in many fields and has earlier been used to model goniophotometric data from reflectance samples (Fairchild et al., 1990). We utilize a variation of PCA for three-way data structures, consisting of the intensity data for each of the

two spherical angles, for each of the measurements to be compared. This extended PCA method is called PARAFAC (Bro, 1997; Bro et al., 1999; Kiers et al., 1999).

In combination with the present comparison, a wireless sensor platform for auxiliary measurement is being tested. This is used in order to ensure that any time dependent behaviour present during measurement of the DUT will not affect the final measurement result. However, this paper will focus on the preliminary comparison, and details of the wireless monitoring platform has been presented by Thorseth et al. (Thorseth et al., 2015).

2 Method

The method used in this comparison is in summary: Each goniophotometer facility is used to measure the LID of a relatively simple (Lambertian) distribution, from a DUT with high light output (≈ 9000 lm). The measured LIDs are then compared with respect to derived quantities and then analysed by the PARAFAC principle component method. The comparison of the measured data includes the quantities total luminous flux, maximum intensity, and the full with half maximum (FWHM) angle of the LID in specific C-planes, while the PARAFAC method is only used to investigate the relationship between measurement data.

2.1 Measurement facilities

In this preliminary comparison three different types of goniophotometer facilities are used. The first, F1, is a traditional far-field C- γ mirror-goniophotometer with a photometer head placed at a distance of $D = 20.7$ m. In this goniophotometer the DUT can be mounted in the operational orientation and during the measurement it is only rotated around the gravitational axis. It accommodates artefacts up to $\varnothing 1.7$ m. This is the type of goniophotometer that is referred to in (CIE, 2015). The second facility, F2, is provided with a camera based nearfield goniophotometer, also equipped with colour matching filters making it a goniocolorimeter. It is type C in which the artefact can be positioned in the desired operational orientation and it is stationary in this position during the measurement. It accommodates artefacts up to $\varnothing 2$ m and the photometer is at a distance of $D = 1.4$ m, making it a far field goniophotometer for small artefacts, $< \varnothing 0.14$ m. The third facility, F3, is provided with a goniospectroradiometer where the distance, D , can be changed and set for the actual measurement. In this study, a distance of $D = 7$ m was chosen. It is a horizontal type C goniospectroradiometer in which the artefact during the measurement is rotated around the optical axis. For this third facility the orientation of the heatsink fins are turned during the measurement causing changes in the thermal environment for the artefact. The facilities vary in operation in several ways, in measurement distance D , operational orientation and the method of light measurement, where illuminance or spectral irradiance is measured. The facilities and measurement identifiers are summarised in Table 1.

Table 1 – The goniophotometer facilities and measurements

Facility	Measurement
F1: C- γ Mirror-goniophotometer	4
F2: Near-field goniophotometer	1 and 2
F3: Type C horizontal goniospectroradiometer	3

2.2 Artefact

A remote phosphor LED luminaire is used as the artefact or device under test in this study. It is a stage and studio lighting luminaire with a replaceable fluorescent front plate, covering an array of blue LEDs. This was selected to compare one of the simplest available distributions, the Lambertian. However, the heatsink of this luminaire has a clear directionality making it susceptible to rotations about axis perpendicular to the direction of gravity. The DUT, shown in Figure 1, has a flat emission area of 356 mm x 275 mm. A remote phosphor plate yielding a correlated colour temperature (CCT) of 5600 K and a colour rendering index (CRI) of 93 is chosen. The total luminous flux is approx. 9000 lm at a power of 160 W. The artefact challenges various aspects of the measuring facilities. For instance, the high CCT can cause

errors in photometers with high spectral mismatch (f_1') (CIE, 1987). The smooth LID may reveal unevenness in the measurement responsivity of the setup. In this study, high intensity gradients are not considered, since the chosen LID does not contain such high gradients which otherwise can cause errors in facilities with low angular resolution.

2.3 Measurements

The measurements were done using the three different types of goniophotometer facilities, (see section 2.1). In all the facilities the DUT was aligned in such a way that the centre of the luminous area was in the centre of goniophotometer systems and the normal to the luminous area was in a horizontal direction. The luminaire is rotated so that the fins of the heatsink are the vertical orientation. This corresponds to the normal operation orientation of the luminaire in a studio setup. In the F3 facility the orientation of the DUT is changed during the measurement. The photo of the DUT in Figure 1 shows the alignment in the F2 facility. Here it is equipped with two auxiliary optical sensors that are mounted on the DUT to monitor the intensity in two directions independent of the movement of the DUT. They are part of the wireless monitoring platform (Thorseth et al., 2015), which also monitors the temperature at two positions of the DUT as well as the orientation of the DUT. Measurements have been done both with the auxiliary sensors in place.

Measurements were started when the measurement equipment and the DUT had achieved stable operation conditions. The latter is ensured by monitoring the power consumption and the light output, e.g. intensity in a given direction. The photometer in the facility or the optical sensors of the wireless platform can be used to measure this as a function of time. The electrical parameters including the power are logged throughout the measurements. The condition for stable operation is, according to CIE S025 (CIE, 2015), that the relative difference of maximum and minimum readings of the intensity and power observed over the previous 15 minutes is less than 0.5%. The DUT must be operated for at least 30 minutes and it is pre-burned in some of the measurements.

The comparison in this study includes two independent measurements in the near-field goniophotometer and one from each of the other facilities. Table 1 provides the overview of the different measurements and the used facilities for these. The angular resolution of the measurements differed in the three facilities, and the results were interpolated to the same angular resolution for the comparison.

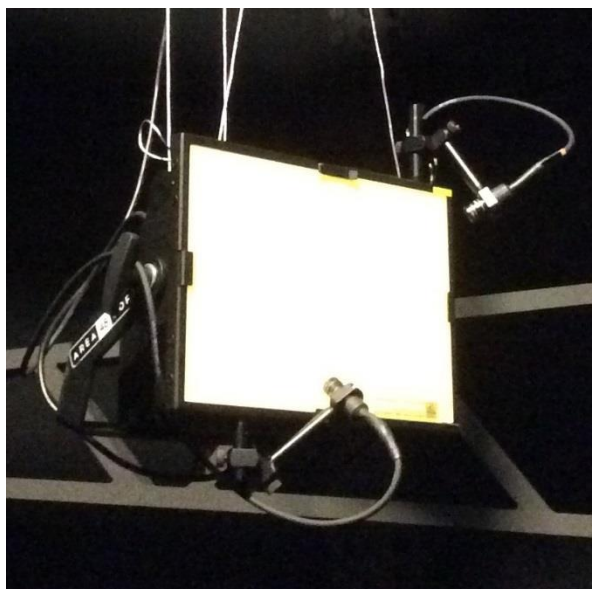


Figure 1 – Photograph of the artefact used for the comparison, here in the F2 near-field goniophotometer facility with the axillary monitoring sensors installed.

2.4 Comparison method

A common approach is to compare LIDs two by two, using a reference LID and a test LID, yielding the individual differences, of various aspects (Gassmann et al., 2015). However, comparing several LIDs, without a well-established reference LID might present problems, when trying to apply this particular method. We will show how this obstacle can perhaps be overcome by comparing large amounts of distributions using a statistical approach. In this paper it is investigated whether the PARAFAC method is a possible candidate for such an analysis.

2.4.1 Principal components analysis

As recommended by (Gassmann et al., 2015) the measured light intensity distributions were prepared for the comparison by rotating the coordinate systems to be overlapping and the intensities were interpolated to the same angular resolution (solid angles of $2.5^\circ \times 2.5^\circ$). From this prepared data, a dataset can be constructed containing I C-angles and J gamma-planes for every one of K goniophotometric measurements. This data structure is ideal for study with a three-dimensional principal component analysis PARAFAC (Bro, 1997; Bro et al., 1999; Kiers et al., 1999), which is freely available as a MATLAB library for download (Bro, 2002). The method models the data in a given three-dimensional array in terms of modes, each with a number of orders. These modes can then be multiplied to recreate the original data, with increasing orders recreating the data with an increasing precision. The method was originally invented for analysis of spectral variations in materials, within chemistry; however, we will investigate its usefulness for analysis of multiple, goniophotometric measurements of assumed equal validity. The PARAFAC method recalculates a point in a given three-way data set to the following form

$$x_{ijk} = \sum_{f=1}^F a_{if} b_{jf} c_{kf} + e_{ijk} \quad (1)$$

Where

- x_{ijk} is the intensity in the i th gamma-angle, the j th C-angle of the k th measured distribution
- F is the number of orders
- $a_{if} b_{jf} c_{kf}$ are the model coefficients of the PARAFAC model
- e_{ijk} is the residual

The PARAFAC algorithm seeks to minimize the residual e_{ijk} . The method describes the data in a three-dimensional x_{ijk} array in terms of modes. These modes can then be used to reconstruct the original data, with increasing number of modes recreating the data with an increasing precision. This means a very drastic reduction in the number of data points in the model, compared to the original dataset, which holds $I \times J \times K$ data points, while the model contains $F(I + J + K)$ parameters. In the present data set with $I=144$ $J=73$ $K=4$, and $F=2$, the method reduces the number of numerical values from 42048 to 442. Another advantage of the method is that the model solutions are unique, since the computation does not include stochastic processes. This approach may provide another perspective on the compared data while avoiding the need for an authoritative reference measurement. Here we use two modes to model the measured data, which may sacrifice high precision for visual clarity of the results. The results of the analysis can be seen in section 3.2.

3 Results and discussion

Here we show the results obtained from measurements with various plots and present the results of the comparison using the PARAFAC method.

3.1 Distributions

Intensity distributions are inherently difficult to visualize, a problem akin to that of geographical map projections. Here we use one-dimensional polar plots, one-dimensional Cartesian plots and heat maps, to visualize the LIDs. Figure 2 shows the luminous intensity in the same gamma plane measured with the different setups. The distributions are clearly of a

similar shape, however, it is seen that the scaling differs by a visible amount. The two dimensional signal of the spherical data can be seen and visually in compared in Figure 3. Here it can be further noted that measurement 1 and 2 share a certain structure, indicating perhaps a systematic error in the measurement relating to the measurement facility (which is the same in these case). Figure 4 shows the same gamma planes using Cartesian coordinates to more clearly show the behaviour in the low intensity regions.

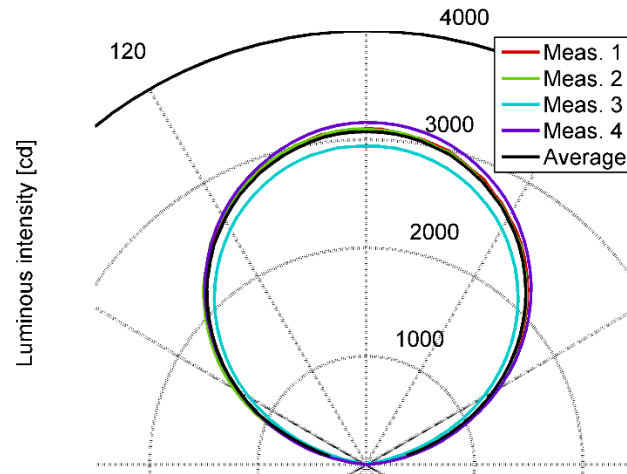


Figure 2 – Intensity distributions [cd] visualised with gamma-planes in a polar plot (as a function of angle), along with the average of the measurements

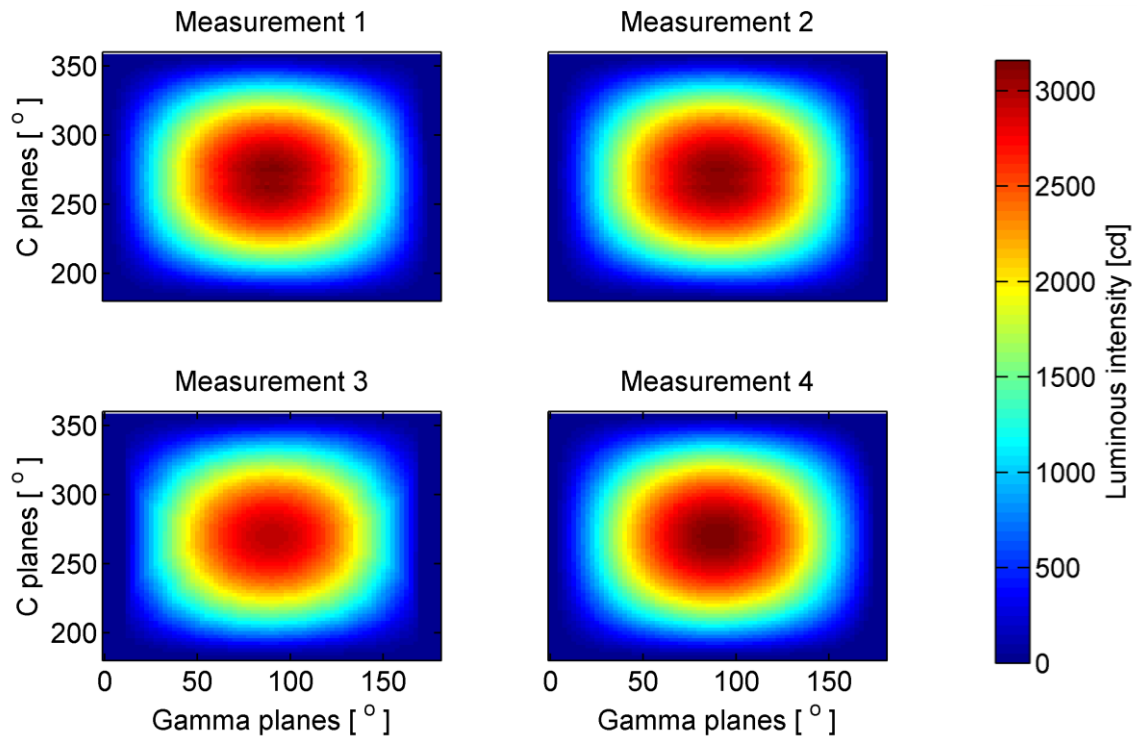


Figure 3 – Distributions shown as heat maps

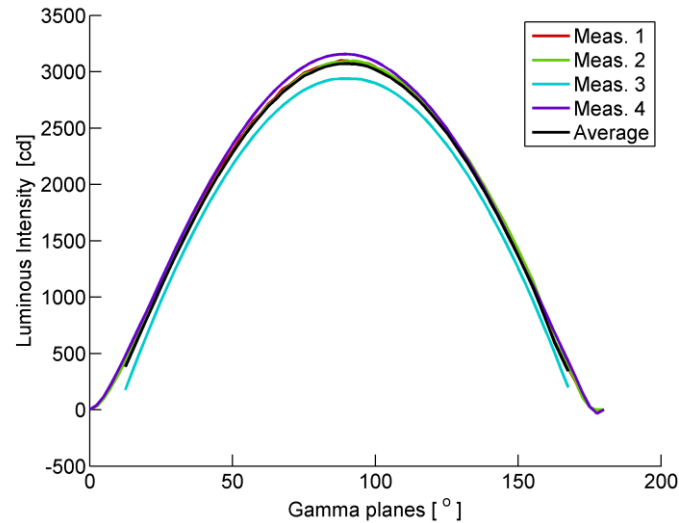


Figure 4 – Distributions shown in a Cartesian plot

3.2 Numerical comparison

The above figures can serve for a visual comparison, which can be used to spot both subtle and significant differences, however, sometimes numerical differences can be difficult to see visually, for instance when comparing multiple distributions. In this section the numerical comparisons are presented. One method of comparison is to show the deviation from the average, this is shown in Figure 5. Here a clear asymmetry can be noted in the calculated difference.

Another comparison method is to look at various derived quantities. Here we will only look at a few, but a comprehensive list of ways to compare quantities derived from intensity distributions can be found in (Gassmann et al., 2015). Table 2 shows the table of derived quantities. It can be noted that the standard deviation on the luminous flux is 3.0%.

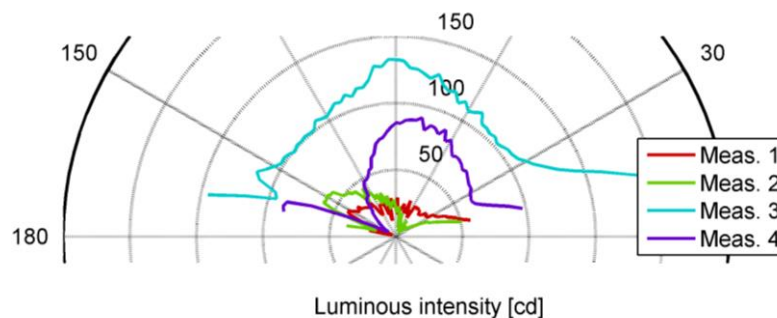
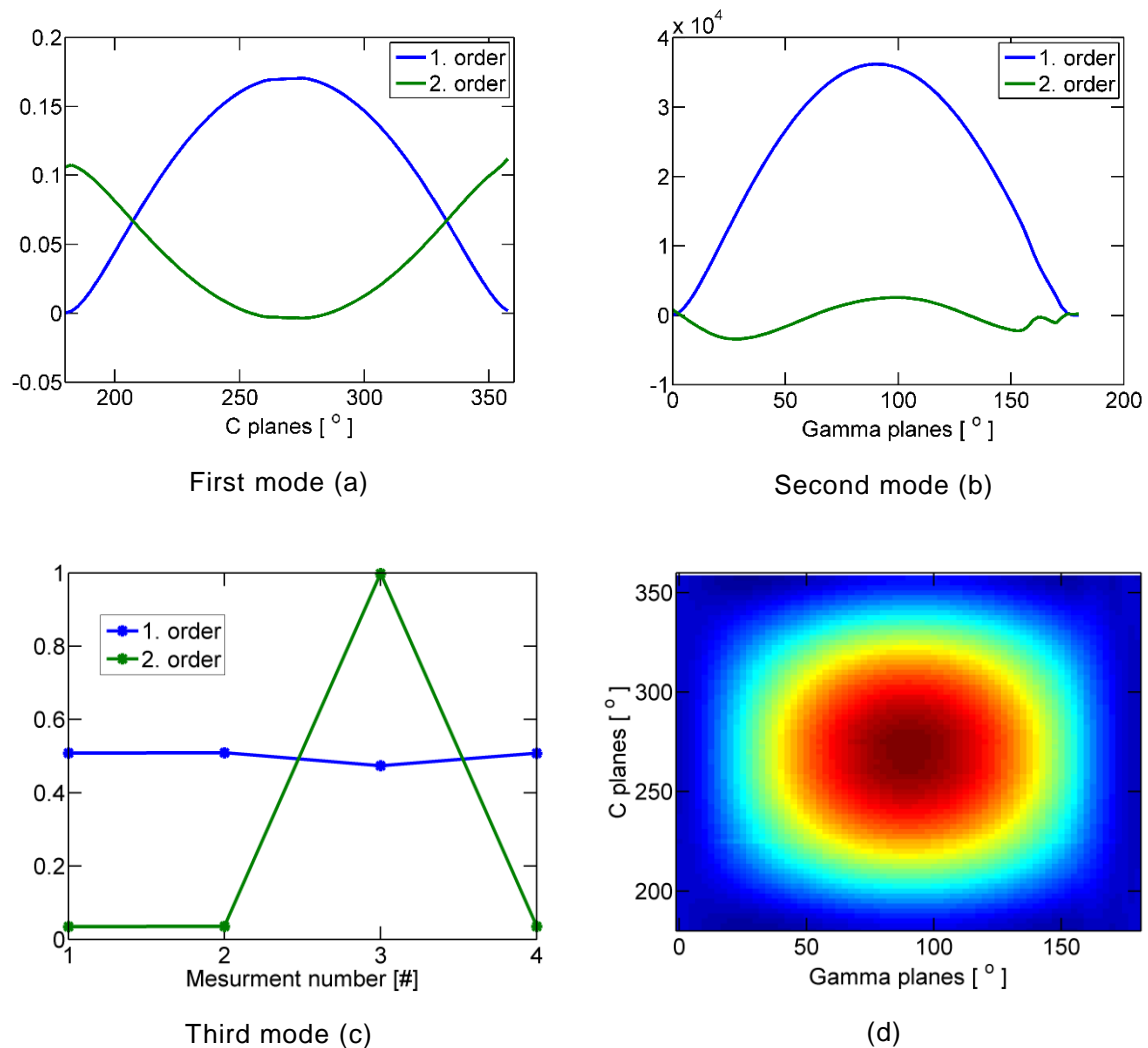


Figure 5 – Absolute difference between luminous intensity [cd] of measurements in a single plane and the average over all measurements

Table 2 – Derived values from the intensity distributions, including the values for the average of all the distributions

	Meas. 1	Meas. 2	Meas. 3	Meas. 4	Average dist.
Luminous flux [lm]	9090	9100	8460	9050	8920
FWHM of Gamma plane 272.5° [°]	114	114	112	113	113
Maximum intensity [cd]	3130	3110	2950	3160	3080
Luminous flux/maximum intensity [lm/cd]	2.904	2.926	2.868	2.864	2.896

**Figure 6 – Results of the PARAFAC three-way principal component analysis, using two orders ($f=2$), showing C-planes as first mode (a) and Gamma-planes as second mode (b) , measurement number as the third mode (c) and a reconstruction of the first measurement using only the model parameters a_{if} , b_{jf} and c_{kf} .**

The result of the PARAFAC analysis is shown in Figure 6. The most prominent principal component found from all the distributions is shown as a blue curve in the first and second mode, describing the distributions changes with angle. The deviations from this, the first order component is shown as the green curves, which represents the higher order $f=2$. The third mode describes the data changes between measurements giving an indication of a scaling of the individual measurements, which comes very easily from this model. The second order

signal might look considerable; however, it should be considered that the multiplication of all the second order modes yields a relatively low contribution. Here the second order terms is clearly dominated by measurement 3. It can perhaps be of interest to study these residuals, which indicate how the distributions differ across the dataset. Figure 6d shows the resulting distribution using the model parameter from measurement 1, for comparison with the data shown in Figure 3. This modeled distribution has a FWHM of Gamma plane 272.5° of 114.5° , which can be compared to the values in Table 2. It should be noted that in the PARAFAC model we do not scale the intensity data according to solid angle, which might influence results derived from the model.

4 Conclusions

We conclude that the three types of goniophotometer facilities produce equivalent results with deviations within a relatively small range. Further, we conclude that the PARAFAC method can be used as a tool to compare a larger number of distributions without the use of a reference LID. The standard deviation in the third mode first order (indicating a scaling factor) is 3.4% while the standard deviation on the luminous flux is 3.0%. So here, we see a good agreement between the model parameters and the derived quantities. Similarly for the FWHM that also yield very similar values for both measurements and model.

On the basis of this pilot comparison, our future work will be to seek to include more facilities in a bigger comparison with more artefacts and seek to investigate, modelling of goniospectroradiometric data with a four-way PARAFAC method. We will also compare the results of this comparison with results obtained by using the methods of Gassmann et al. Further investigations could also be made into the rigidity of the PARAFAC method under various disturbances such as small rotations or simulated noise.

Acknowledgements

This work was made possible by the grant for “Center for LED metrology” from Innovation Fund Denmark.

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