FINAL PUBLISHABLE REPORT

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1 Overview

LED-based lighting products are the most rapidly evolving light sources on the market for general lighting in urban areas or domestic dwellings. Due to spectral and geometrical peculiarities, SI traceable measurements of LED-based light sources are much more difficult than those of traditional tungsten filament lamps or fluorescent light sources. This makes it difficult for test laboratories to evaluate application-relevant properties using existing measurement methods and standards developed for incandescent light sources. Standards for traceable test methods exist but important metrological aspects for their practical application had not yet been fully considered before this project. For example, the assessment of uncertainty, intensity distributions of luminaires as well as spectral measurements, had yet to be resolved. This project identified essential test parameters, develop validated procedures and good practice guidelines for test laboratories and helped to shape the upcoming revisions of CIE S 025/E:2015, ISO/CIE 19476:2014 and EN 13032-4 standards.

2 Need

Reliability and validity of product specifications are of great importance in the general lighting market, which is unsettled by unfulfilled performance promises of cheap lighting products. Trust can only be rebuilt if test laboratories can deliver reliable SI-traceable test results of photometric quantities, which meet the demands of industry and customers, for a large range of diverse LED-based light sources. Statements on uncertainty assessment to improve the evaluation of LED products became mandatory in the first worldwide accepted standards CIE S 025/E:2015 and EN 13032-4 on test procedures for LED based lamps, luminaires and modules published by the International Commission on Illumination (CIE) and the European Committee for Standardization (CEN). However, these standards are incomplete, as there was still no validated procedure available to assign measurement uncertainties, at test laboratory level, for some listed measurement quantities and metrological procedures.

Requirements and boundary conditions for precise image-based luminance measurements and concepts for evaluating the uncertainty of typically correlated spectral measurement data are of high importance for test laboratories to determine the real performance of LED-based sources. Although prerequisites for the application of the standards are well established, respective guidelines were not available. Moreover, a suitable harmonised metric including associated tolerances for a target/actual performance comparison of luminous intensity distributions of LED-modules or luminaires was also missing.

Photometers are ubiquitous metrological devices in lighting, being used by a wide range of lighting professionals from designers to electricians, for testing installations on performance, compliance and utility. But these meters typically include significant errors that cannot be neglected, namely in the measurement of LED-based lamps. To estimate the spectral mismatch of the response of the photometers (in relation to standardised efficiency of the human eye) within a measurement setup, the so called f1’ index defined in ISO/CIE 19476:2014 can be used according to EN 13032-4. However, the metric i.e., the mathematical equation for determining f1’ is deemed to be not the most appropriate for LED light sources. Therefore, for the revision of ISO/CIE 19476:2014, CIE S 025/E:2015 and EN 13032-4, it had to be clarified under which conditions the mismatch index can be used in the measurement of LED light sources in the future and how the newly defined LED reference spectrum can be integrated here.

The CIE identified these issues as being part of their research priorities.

3 Objectives

The overall goal of the project was to deliver metrics and procedures as well as guidance on metrology issues, and to made existing CIE and CEN test standards for LED-based light sources applicable to testing laboratories as a whole. The specific objectives were:

1. To develop a strategy for the evaluation, validation and traceability of spatially and angularly resolved luminance and luminous intensity distributions of LED-based lamps, luminaires, and modules. This should be based on measurements using imaging luminance measurement devices (ILMDs). Additionally, to develop guidelines on the determination of uncertainty and tolerance intervals required in the revision of CIE S 025/E:2015.
2. To develop guidelines on the estimation and uncertainty of i) the spectral mismatch of integral (filtered) measurements for sources emitting coloured light, and ii) integral quantities derived from

spectral measurements. Additionally, to propose an extension of CIE S 025/E:2015 and EN 13032-4 for an alternative spectral mismatch quality index, based on the new LED reference spectrum published in CIE 15:2018 for white LEDs.

3. To propose a harmonised metric to compare luminous intensity distributions, including the definition of the associated tolerance intervals and uncertainties, with a focus on test methods that require the declaration of measurement uncertainties.
4. To contribute to the revision of CIE S 025:2015 / EN 13032-4 through CIE Division 2, CEN/TC 169 and IEC TC 34. Outputs should be in a form that can be incorporated into the standards at the earliest opportunity and communicated through a variety of media to the standards community and to end users. Additionally, to promote the take up of the results by end users e.g. manufacturers of LED-based sources.

4 Results

According to the project objectives, the aim of the work was to provide guidance for laboratories and suggestions and guidelines for standardisation bodies on some unresolved metrological issues related to imaging luminance meters (ILMDs), spectral meters and luminous intensity distribution setups.

4.1 Evaluation, validation and traceability of spatially and angularly resolved luminance and luminous intensity distributions

Imaging luminance measurement devices (ILMDs) are powerful instruments, which are now being used in more and more applications, therefore replacing classical point luminance meters. Near-field goniophotometry, although not explicitly mentioned in this project, is also based on ILMDs and is an emerging technique for determining the spatial and directional-dependent luminance and luminous intensity distribution of sources. In order to be able to provide traceable measurements with an ILMD, its systematic errors and related uncertainty contributions must be assessed.

In the first stage of the project, the partners performed a series of selected characterisations on their ILMD systems (see image below). TUBITAK focused on properties of dark noise and shading. LNE characterised their ILMD regarding the non-linearity properties using luminance images, detection limit and homogeneity. PTB did experiments on the stray-light effects (offset, ghost images, diffraction spikes) using a pixel sized luminance source and a positioning system (Fig.1). The second topic worked on by PTB was non-linearity, especially with the discrimination between three different internal sources for non-linearity: a “general” one coming from the internal signal processing, and two sources that originate in the charge accumulating mode of the image sensor. One is an effect of the I-V curve of the pixel diode itself, which get relevant at very long integration times. Results from this were presented at the CIE Midterm Conference 2021. The second effect is a spectral dependent non-linearity which relevance depends on the sensor model. These results were published as a paper at the CIE Quadrennial Session 2023.

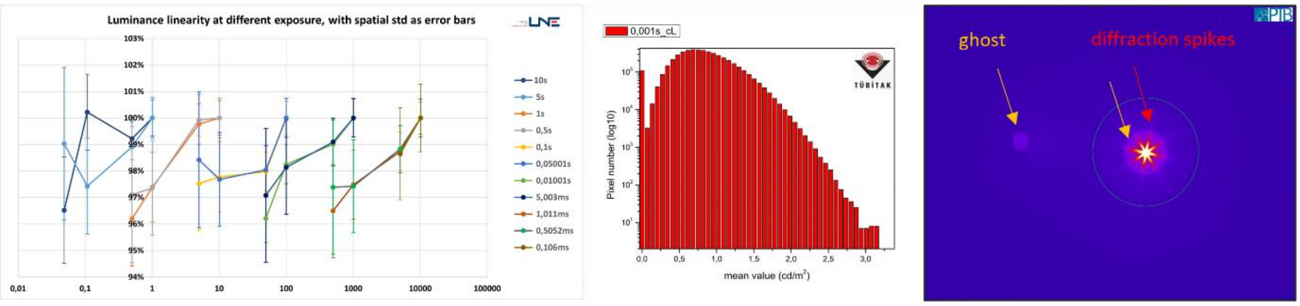


Fig.1: Characterisation of ILMDs regarding linearity (left), dark noise (centre) and stray-light effects (right)

The project partners discussed the results and details of all these investigations, regarding the requirements to determine parameters and their usefulness. If there is access to unfiltered, internal count signal images this is useful to characterise internal properties, like system gain. But this access is only available for some device models. Other devices may do some pre-processing of the data, that hinders the usefulness of such raw data. If resulting luminance images are evaluated instead as a reading indicated by the ILMD, certain effects are altered by internal corrections with respect to parameters adjusted by the manufacturer, while some additional artefacts may come from clipping and smoothing operators. Pixelwise interpretation of the noise and back-propagation to properties of an internal model, therefore turned out not to be useful for the operator in calibration and testing laboratories.

In parallel to this experimental work, a list of measurement applications were collected by TechnoTeam with contributions from other partners to define different classes of applications for which different calibration-/characterisation strategies can be implemented. But with a deeper understanding this turned out not to be helpful. ILMDs are versatile instruments that are usually applicable to a broad range of applications. To limit the characterisation effort to a specific measurement application would also limit its applicability to exactly this one. On the other hand, it is easy to change a measurement configuration from one where some effect can be neglected to one where it can't. Therefore, the idea of splitting characterisation strategies at this stage was dropped and the examples of the application list were used to illustrate the decisions and which effects are considered relevant.

The project aimed to determine systematic effects and correct for them, as per the "Guide to the Expression of Uncertainty in Measurement" (GUM), (JCGM 100:2008). This handling of the systematic effects involves the determination of the functions that describe the effects and then their use to calculate the corrections for a specific operating condition of the device. But this leads to different issues . The user of an ILMD has only limited access to internal parameters or intermediate values. Even raw count signal of the sensor might not be accessible. Then, the device may implement different pre- or post-processing steps and apply corrections for some effects internally in order to provide a luminance signal. If the users use the ILMD "as is" (as they are proposed to do), then only the superposition of multiple residual effects is visible in the measured data. To determine the *individual component* of this superposed mixture that originates only from one specific effect, only a few ways for a targeted stimulation of the system are possible. Most of them rely on the change of the measured scene. And this is hardly possible without changing multiple properties at once. This would lead to determined functions that are not describing the individual component but still a mixture. Here is a high risk to do lot of characterisation effort without actual benefit to correct for systematic errors present in the luminance signal.

If the users have access to the raw count signal that has not undergone corrections and uses this to characterise the individual functions describing the systematic effects, they have the advantage to get a stronger effect but on the other hand they must do all the calculations from count signal to a luminance result themselves. This approach also relies on the permanence of internal settings or the knowledge of internal changes of the operating condition, but manufacturers usually don't publish device-internal details. Another consequence would be that the users could not use the ILMD software as an integrated part for the extended evaluation of the luminance images.

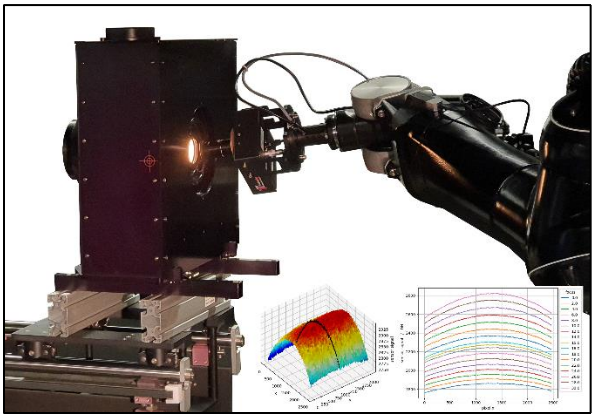


Fig.2: Setup for calibration and characterisation of ILMDs with 6 degrees of freedom during positioning

As part of the project, count images were used to implement a calibration procedure for ILMDs. The experience gained was used to simplify the procedure. With the help of the set-up for characterising ILMDs (Fig.2), knowledge about the properties of ILMDs was gained and transferred to the luminance signal images available to the user. PTB set up a model of evaluation, covering the internal steps of imaging, charge generation and accumulation in the sensor and signal processing that convert the spectral irradiance (with an assigned luminance) in a scene into a count value. The model covers effects like non-linearity, shading and photo-response non-uniformity, focus dependence of shading and offsets. The second part of this model covers its inversion to derive the luminance value from the count signal value, with the need to replace intermediate quantities of the first part by ones that are accessible to the user and take care for the right order of applying corrections. This calibration procedures were implemented and applied to available ILMDs by PTB (see image left for shading effect). Only the thorough determination of the spectral responsivity could not be realised, but its characterisation at a set of wavelengths by TUBITAK confirmed the spectral responsivity specified by the manufacturer. From these calibrations, information, it can be derived on how the effects could be corrected and under which critical conditions residual errors of an ILMD can be expected, depending on the complexity of the correction.

As stated before, initially the prevailing idea was to correct for systematic errors. Taking into consideration that there are other complex measurement devices like Coordinate Measurement Machines (CMM), similar procedures were sought for dealing with the measurement uncertainties for ILMDs.. It turned out that the common solution for CMMs is to just measure calibrated length standards in the working volume to determine "typical" errors that one can expect, not to try to determine residual errors and correct them. Only a few manufacturers implement a "Virtual CMM" in their devices which allows the assessment of measurement uncertainty using knowledge of the internal state of the device and the correction functions used by the manufacturer. As such, the project decided that the correction of systematic errors was not most useful to operators and that systematic errors should instead be included in the calculation of uncertainties as a separate uncertainty contribution.. With this simplification and the knowledge on critical measurement conditions, strategies for relatively simple estimations of residual uncertainty components could be derived. To make this complexity understandable and permanently available for the user, a two-part Good Practice Guide (GPG) has been developed.

Part 1 of the GPG from PTB deals with the handling and estimation of measurement uncertainties at critical measurement configurations arising from the operating principle of an ILMD with internal corrections and considers their relevance for selected examples of the collected measurement applications with aspects on correlations between multiple measurements (inside one or between subsequent luminance images). It is shown how information from the device manufacturer about the properties of an ILMD can be used for such estimations. Detailed contributions to the measurement with an ILMD and its uncertainty, i.e. mainly from the scene and the definition of the measurand in the application and its repeatability, are covered in Part-2 of the GPG from TechnoTeam. As both guidelines can only be applied meaningfully if a proper condition and configuration of the ILMD is ensured, an appendix has been prepared that provides a checklist for the correct configuration of ILMDs to ensure absence of mistakes or errors which cannot be covered by an uncertainty estimate. This checklist was also part of the hands-on training session on the calibration and verification of ILMDs held at PTB in May 2023, where roughly 30 participants from industry, universities and NMIs took part and contributed to discussions. This hands-on training was also used to take the needs of the participants into account in the GPG and included practical sessions about characterisation of absolute and relative luminous responsivity (focus dependence and shading), stray-light (size of source effect and negative contrast) and non-linearity of ILMDs as well as errors in ILMD measurements arising from temporal light modulation. In delivering the training and writing the GPG, PTB and TechnoTeam were supported in particular by LNE, TUBITAK and the collaborator Instrument Systems. Beside the GPG available from the download-area of the website of the project, the intermediate and final results were presented at the CIE Midterm Conference 2021 and the CIE 30th Quadrennial Session 2023 and are available in the conference proceedings. A detailed paper on the calibration methods for ILMDs summarising the two parts of the Good Practice Guide will be made available in a reviewed journal.

In summary, it can be stated that the objective of providing methods for traceable spatially and angularly resolved luminance and luminous intensity distributions for the general user of ILMDs has been achieved from the general user's point of view, whereby the user is responsible for recording the influences of these deviations from the manufacturer's calibration conditions in the context of test measurements and adding them to the manufacturer's uncertainty budget as an uncertainty component.

4.2 Guidelines on the estimation and uncertainty of the spectral mismatch and integral quantities derived from spectral measurements

This project's initial aim was to support measurement technicians in test laboratories by showing them ways to take correlations into account in their measurements. Taking into account the (often complex) correlations within spectral measurement data when calculating integral quantities is still a missing part in dealing with uncertainties. In most cases, the spectral data are assumed to be uncorrelated, and it is often argued that even if a full correlation were expected - the effect of which can also be easily calculated, since the combined uncertainty simply changes from the square root of the sum of the squared individual uncertainties to the sum of the individual uncertainty components - the combined uncertainty would not change very much. However, investigations made by Aalto in the framework of this project, utilising the concept of data variation using orthogonal functions, showed that partial correlation of spectral data has a much higher impact on the combined uncertainty of integrated quantities than expected, as compared with uncorrelated or fully correlated spectral data. In order to present this in a comprehensible way, a generic approach was used to calculate integral quantities derived from measured spectral data. The results were presented at the 30th CIE

Quadrennial Conference [3] but the results can also be traced with the help of the deposited code in the project's GitHub repository (see below).

The consortium agreed that the only reasonable solution for dealing with correlations in spectral measurements was the consistent use of Monte Carlo methods – although knowing that there is much reluctance in the community to do so. In order to make it easier to get started with new methods - and here, Monte Carlo methods for calculating uncertainties were the most important - the idea came up at the start of the project to provide exemplary codes that can be used by readers to write or adapt their own evaluation programmes. Instead of relying on commercial software, the freely available Python programming language was chosen from the outset, which, together with the freely available Jupyter Notebook from Project Jupyter, forms a simple entry-level platform for which a large number of high-quality modules and libraries are already available for the fields of photometry and radiometry. The project's GitHub repository has examples for all objectives of the 19NRM02 RevStdLED.

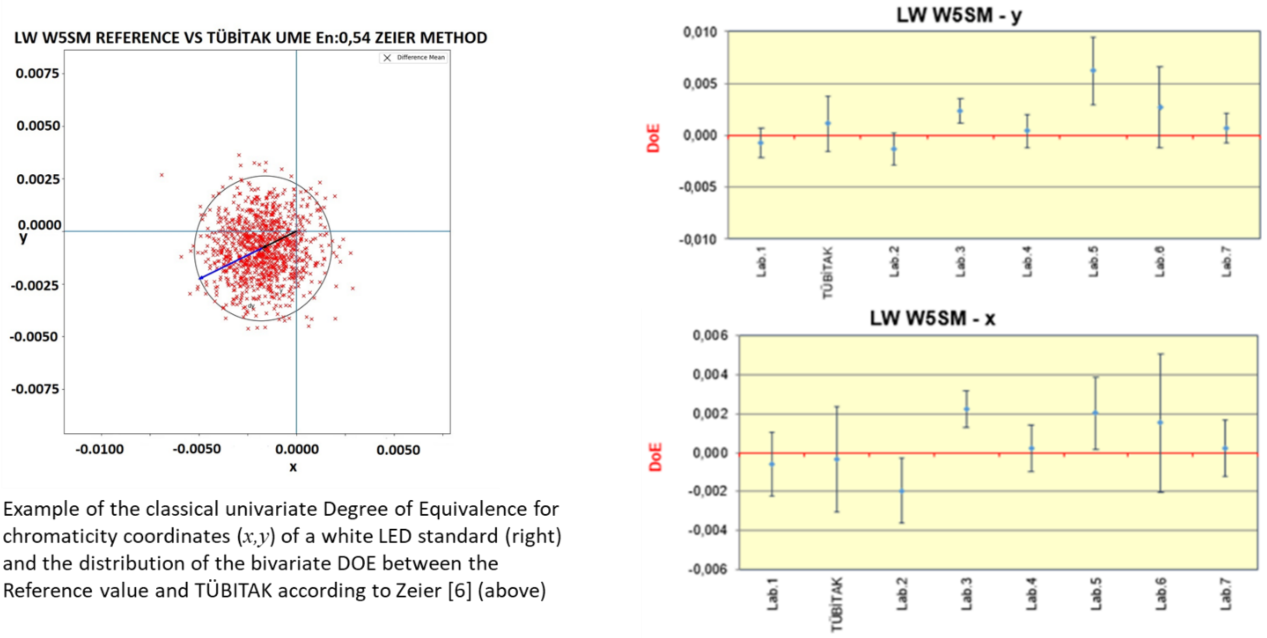
The status quo on the traceability of spectral quantities at the beginning of the project was summarised by the participating NMIs in a summary report collected by LNE. With the aim to harmonise the different approaches used by participating NMIs, a guideline on measurement uncertainties and distribution of correlation matrices was provided by LNE, PTB, Aalto, TUBITAK, IPQ, and NMISA which shows the traceability roots and the treatment of measurement uncertainties also under consideration of Monte Carlo simulations. The evaluation models used in this guide are also partly used in a software code written in Python by PTB, which in particular shows approaches to consider correlations. This software has been distributed within the consortium and is also available via the project's GitHub repository. The various codes delivered on GitHub are of different levels of complexity. In the repository WP2-examples the examples given are based on PTB's approach to determine the uncertainty for luminous responsivity and spectral radiance responsivity, which uses merely simple and generic Python modules. This is helpful to become familiar with Python. It also shows in detail, how joint probability distributions functions (PDFs) are generated stepwise from marginal distributions (i.e. uncorrelated datasets) using the concept of copulas. In contrast, the advanced examples in the Python Toolbox, coded by TechnoTeam with feedback from DTU, PTB, Aalto, LNE, TUBITAK, use advanced Python modules (in particular LuxPy) for calculating photometric and radiometric quantities and additional mathematical, statistical and graphical modules to focus on solutions to the problems addressed, such as the boundary conditions for uncertainty of spectral mismatch, f_1', uncertainty of chromaticity coordinates, multidimensional degree of equivalence, etc. (see below). Python provides all the necessary tools to handle vector quantities, as the spectral quantities are understood here, and large covariance matrices, including procedures to clean up so-called "ill conditioned" matrices to generate the necessary positive semidefinite covariance matrices for further processing and transmission.

PTB, LNE and NSC-IM developed a guideline on working procedures and the requirement of specifications of measurement setups for test laboratories for the photometric quantities: luminous responsivity, luminous intensity, chromaticity coordinates and luminous flux. The guide was originally intended as a basic document for conducting an intercomparison between the project partners for luminous intensity, luminance and chromaticity. Six LED-based standard light sources, two white ones for luminous intensity and three coloured and one white for luminance, were prepared by PTB and TechnoTeam for this purpose (see Fig.3). The aim of this comparison piloted by TUBITAK was to compare the different abilities of the participants in respect to spectral correlations. However, due to the Covid pandemic and the war in Ukraine, the schedule was completely corrupted, so that the comparison had to be carried out independently and with fewer participants than originally planned. Due to time constraints, only TechnoTeam, Jeti, candelTec, CSIC, LNE, TUBITAK, NMISA and PTB could take part. In addition, spectral correlations were only taken into account with respect to the correlation of the chromaticity coordinates. Nevertheless there was still novelty, as TUBITAK with the support of TechnoTeam determined results of the chromaticity coordinates of the LED lamps and their uncertainties for the first time, not only according to the classical GUM, (JCGM 100:2008), as independent coordinates, but correctly taken as multivariate quantities (JCGM 102:2011), to which an approach for determining the 2-dimensional Degree of Equivalence (DoE) was provided in the Python Toolbox. Unfortunately, a more detailed examination of the results was no longer possible due to time constraints of the project, i.e. the results were compared and documented but the origin of the differences not studied in detail (see Fig.4).

Fig.3:

Luminance standard

Luminous intensity standard



Example of the classical univariate Degree of Equivalence for chromaticity coordinates (x,y) of a white LED standard (right) and the distribution of the bivariate DOE between the Reference value and TÜBITAK according to Zeier [6] (above)

Fig.4: Comparison result oft the chromaticity coordinate for a white LED standard

If one takes the GUM seriously, the concept of a multidimensional DoE for multivariate quantities becomes crucial not only for the two-dimensional case of chromaticity coordinates, but also for spectral quantities when they are described as multidimensional vector quantities. Usually, the statement about the DoE of two spectra should reflect a statement about their “similarity”. However, up to now there have been no approaches to express this. Within this project and based on a state of the art approach, TechnoTeam provided a module for photometry and radiometry in the Python Toolbox and showed first results on sample data. For validation, the Python code was verified with an independently written Octave program from Aalto. The results have not been published yet, but the provided module was used by TUBITAK to analyse the DoE of the bivariate chromaticity coordinates within the intercomparison of the project (see above).

Finally, a GPG for calibration laboratories was developed. This GPG starts with basic information on how to set up a Monte Carlo simulation for a simple photometric example and provides knowledge on how to set up evaluation models as a prerequisite for the application of Monte Carlo simulations. The GPG also contains information from the guideline on working procedures as well as from the guideline on measurement uncertainties. Incidentally, the contents of the guidelines were also the subject of the training organised by PTB and TUBITAK in July 2023 on the topic of "Uncertainty of correlated spectral data" held as an online event with 60 registered participants and in the practical training on the topic of "Spectral measurement methods" conducted and organised at TUBITAK in August 2023 with 23 participants.

As a normative project, in order to forward the project results to the standardisation bodies, close liaison with the main stakeholder CIE was essential. This was achieved by appointing a member of the project consortium as chairman of the new CIE TC 2-97 technical committee, which was established in May 2022 to revise the CIE standard CIE S 025:2015 “Test Method for LED lamps, LED Luminaire and LED Modules”. Moreover, it was achieved that the revision of CEN standards EN 13032-4, which is based on the CIE S 025, is set on halt until the revision of the CIE S 025 is close to final. This is important to ensure that both the international CIE S 025 and the European EN 13032-4 remain harmonised.

In the spring of 2022, a working group was established at the CIE Division 2 Management level to develop suggestions around the topic of how the uncertainty evaluation in CIE S 025 can be made usable for end users. Sharing the approaches of this project and sharing and maintaining the software code on the GitHub repository even after the end of the project will support this.

In summary, it can be stated that the objective of establishing guidelines for the estimation and uncertainty of spectral mismatches and integral quantities derived from spectral measurements has been achieved. It has been shown that the consideration of partial correlations (spectral as well as general) and the use of Monte Carlo methods are crucial for meaningful uncertainty determinations. Particular attention was paid to partial correlations, as their influence was completely underestimated in the past. A documented software code was also provided to promote the adoption of the guidelines.

4.2.1 Investigating the spectral mismatch index

TechnoTeam conducted a literature review on the general $V(\lambda)$ mismatch index f_1', looking at the history as well as the current state and new ideas on the mismatch index that have emerged in recent years. On this basis, a document was prepared and published at the CIE midterm meeting 2021 describing the rationale for a complementing spectral mismatch index for LED light sources and also discussing the possible effects on existing applications and the calculation of measurement uncertainty. This document was further selected for a special issue of the scientific journal Lighting Research and Technology (Krüger et al. 2023).

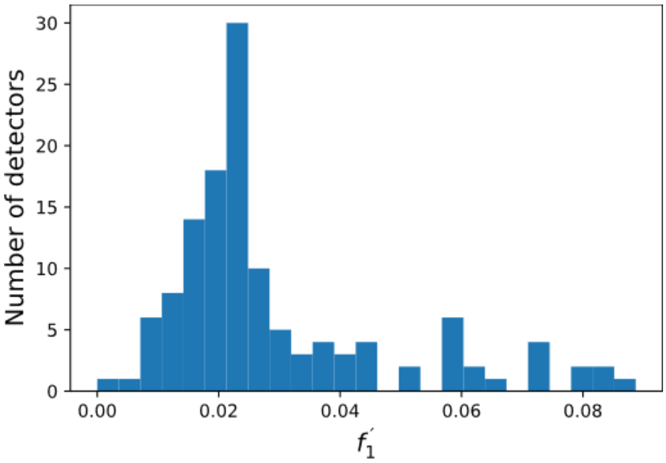


Fig.5: Distribution of the classic f_1' values of the photometers to investigate the need for a complementary f_1' value.

In the next step, TechnoTeam wrote Python program modules and made them available in the Python Toolbox to test the impact of the different approaches for f_1' in the description of the quality of the photometers to be evaluated, to compare and to derive correlations. For this purpose, the spectral data sets of 120 photometers (Fig.5) with different f_1'-values that served as a basis for the annex to f_1' of the CIE S 025:2014, as well as over 1593 spectral distributions of phosphor-based and RGB-based LEDs from the EMPIR project 15SIB07 PhotoLED and from the CIE S 025 were used. The results show that although there are better approaches for the general mismatch index f_1' to predict the spectral mismatch of photometers for certain types of light sources to be measured, these then provide poorer results for other types of light sources. The main weakness of the current general mismatch index was found to be not in its definition, but in the use of Illuminant A as the general calibration source for the photometers. If the photometers were calibrated with the new Illuminant L41 defined in CIE 251:2023 based on CIE 15:2018, the significance of f_1' would generally improve for all light sources (with the exception of Illuminant A), because the spectral distribution of the calibration light source together with the spectral sensitivity of the photometer determines the actual spectral mismatch.

The results of the work on the complementing spectral mismatch index carried out in this project have been forwarded to i) the CIE reportership DR 2-89 on the "Definition of a complementary general $V(\lambda)$-mismatch index", which targets the revision of standards CIE 19476:2014(E) and CIE S 025/E:2015, and to ii) the CIE TC 2-96, which targets the revision of ISO/CIE 19476. These two committees are chaired by members of the project's consortium and were both established within CIE Division 2 in early 2021.

The outcome of the investigations on the mismatch index are also summarised in conference proceedings and peer reviewed journals. All calculations are based on a large data set which also includes data from 15SIB07 PhotoLED (see: https://doi.org/10.11583/dtu.12783389.v1) and can be retraced using the freely accessible software and data via the EMPIR 19NRM02 GitHub project (https://github.com/empir19nrm02)). The results have been summarised in reports and publications made available on the EURAMET repository and the recommendation has been officially forwarded to CIE via reportership DR 2-89 (https://doi.org/10.5281/zenodo.7870877).

To summarise, the investigation of the spectral mismatch index revealed no need to define a complementary index for LEDs. The results were passed on to the standardisation committees.

4.3 Harmonised metric for luminous intensity distribution

As a prerequisite to describe spatial distributions of light, a model for geometrical dependencies of a generic goniophotometer was developed and was presented at the NEWRAD meeting in 2021 and at the CIE midterm meeting in 2021.

In a first approach, the equivalence of measuring the light intensity distribution (LID) of light sources in the far field with a photometer and the measurement of partial luminous intensity distributions on a screen with a luminance measuring camera (ILMD) was demonstrated. The advantage of measuring LID measurements on a screen with an ILMD is the high-resolution acquisition of a large angular range with one image and the resulting correlation within the LID.

For the uncertainty budget, the mathematical model of the system was divided into photometric and geometric contributions. For the analysis of the geometric contributions, a Monte Carlo approach was developed that takes into account the uncertainty of the measurement direction and distance resulting from the geometric components of the measurement. For this purpose, the evaluation model includes the geometric system description of the complete goniometer including receiver based on kinematic chain and its transformation. For the description of the transformation of the coordinate systems of goniophotometer, source and detector, the method of the Denavit-Hartenberg parameters (DH) known from robotics was adopted, whereby it is new that the kinematic chain begins in the detector and ends in the origin of the measurement object.

The propagation of geometric uncertainties, including correlations, is done by successively transforming the coordinate systems of the source and receiver with respect to a device coordinate system, according to the DH parameter methodology. In order to take all relevant input variables into account, the adjustment and measurement process was modelled accordingly, and the analysis of the geometric input parameters was performed with Monte Carlo simulations. The results of the geometric analysis for the case of ILMD-based luminous intensity distribution (LID) measurements using Monte Carlo simulations were submitted and published as a peer-reviewed paper in the Journal of Physics conference series.

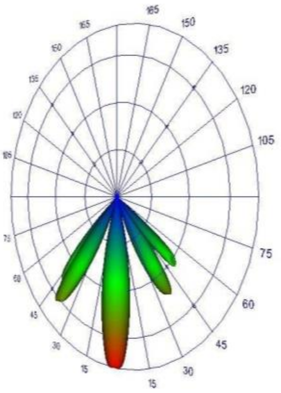


Fig.6: Luminous intensity distribution body of one of the test sources developed.

The published article showed that the pose of the light centre causes the largest contribution in the geometric part of the measurement uncertainty budget and therefore further investigations were carried out on the influence of the light centre on the uncertainty of the spatial luminous intensity distribution. This proved to be crucial for the generalisation of the elaborated method for far-field goniophotometers. To this end, various approaches were pursued to build standard lamps with a defined luminous intensity distribution body, which should make it possible to generate a describable characteristic luminous intensity distribution (Fig.6). In total, three different radiation sources with different properties were developed. The luminous intensity distribution body of the version with five geometrically defined radiation lobes can be seen in the picture on the left. With all three radiation sources, comparative measurements were carried out between PTB and KIT with different goniophotometers in the summer of 2023.

As it turns out, precise knowledge of the actual centre of gravity of the light source is necessary in order to be able to apply the above model for the propagation of geometric uncertainties in principle, as it is a prerequisite for the model of the luminous intensity itself. However, this model of the centre of gravity of light is, on the one hand, direction-dependent and subject to uncertainty, since it depends on the measurement geometry. Due to the principle, the centre of gravity of light can only be determined from measurement data of near-field goniometers. Even with far-field goniophotometers, where the uncertainty of the position of the centre of rotation of the measuring system and the pose of the detector are known, the centre of light of the source cannot be determined for all directions. There is also an inherent error resulting from the ratio of the size of the object to the measurement distance. This error has the same effect as the error from the unknown centre of light, i.e. light coming from locations other than the assumed centre of the meter in far-field goniophotometers. The result is a deviating measurement distance and angle for each measurement direction. The unknown luminance characteristic of the object leads to an uncertainty contribution that can only be determined with the help of near-field measurements. To reduce the uncertainty to an acceptable level, the measurement distance is increased according to rules of thumb. The position of the centre of gravity of the light is not taken into account at all, so that a holistic uncertainty estimation is not possible.

In order to be able to explain the differences in the measured luminous intensity distributions of near-field goniophotometers and far-field goniophotometers, it is therefore necessary to sensitise the users to the problem of the centre of gravity of the light source. The work within the project was therefore concerned with making this uncertainty contribution tangible by showing the influence of the position of the light source's centre of gravity for exemplary LID.

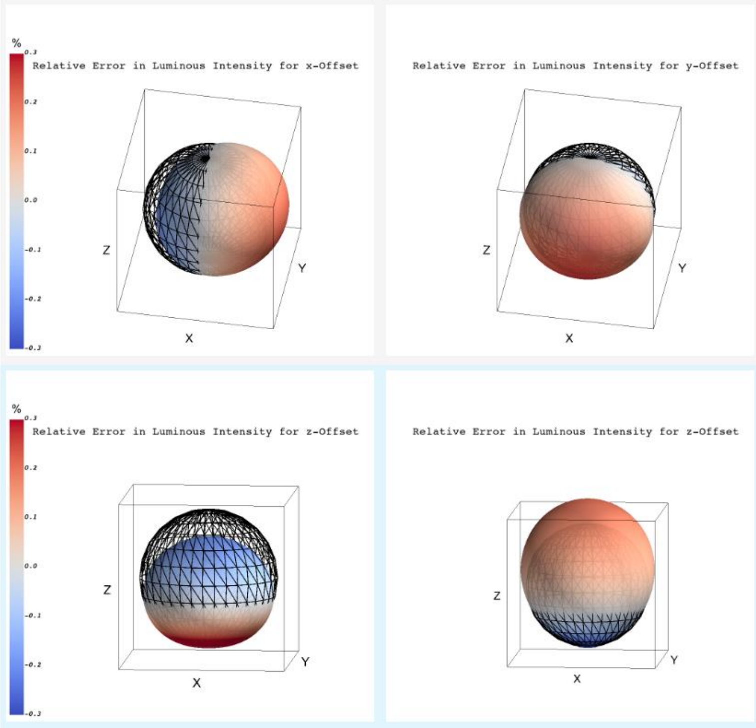


Fig.7: Influence of the centre of gravity of the position of the light source on the LID.

To highlight this issue and as an extension to the first publication on geometric uncertainty, KIT has now provided code in Python for estimating the uncertainty due to the position of the centre of gravity of light in the form of an interactive Jupyter notebook with explanations on the project's GitHub repository. This document explains how to model the uncertainty contribution of the pose of the centre of light in the measurement. It generates interactive plots and calculations of the measurement uncertainty for the input variable of the offset position between the goniometer's centre of rotation and the object's centre of light (see Fig.7). This input variable can be calculated and tracked in this interactive document using a Phyton program. However, due to the operating principle of far-field goniophotometers, it can only be estimated for LID measurements, as the effective centre of light of luminaires, especially for LID with high gradients, cannot be determined in a far-field measurement.

A GPG on how to use the new metric to take into account geometric dependencies and resulting tolerances when determining the light intensity distribution and their uncertainties in goniophotometers will be published on the projects website.

The result of the project shows that the influence of the geometry can be estimated in principle. However, the complexity of a LID due to its high dimensionality (number of dimensions > 3) does not allow a simplified estimation of the measurement uncertainty based on parameters of the LID alone, as assumed at the beginning of the project.

In summary, it can be said that a harmonised metric for light intensity distributions has been developed, but this can only be used without restriction for camera-based near-field goniophotometers. For classical far-field goniophotometers, the quality of the uncertainty analysis depends on the estimation of the centre of light.

5 Impact

To increase visibility, the project website (https://www.ptb.de/empir2020/revstdled) was created shortly after the start of the project.

As the dissemination of results to CIE as the chief stakeholder was of utmost importance, the project focused on the establishment of reporterships and technical committees in CIE under the leadership of partners and collaborators of this project. In addition, various members and collaborators of the consortium are also members of the relevant committees of the national standardising bodies and thus promote the dissemination of the project results to the corresponding bodies at ISO and CEN via national representatives.

The project participated in several national and international conferences, and the works were shared in a total of 21 presentations/posters. Targeted Conferences included Licht2021 and the CIE Mid-Term Conference 2021. A total of 12 posters and oral presentations were given at the latter, including a general overview of the project and two oral presentations at a CIE workshop on the revision of ISO/CIE 19476 and CIE S 025 led by the RevStdLED project coordinator. The status of the work in the project’s work packages was presented at the first RevStdLED stakeholder meeting, which took place on 7 October 2021 with 11 stakeholders from UK, Belgium, Italy, Austria and Germany.

In addition to these dissemination activities, the project regularly informed other key stakeholders of the project, such as the chief stakeholder CIE Division 2, EURAMET TC-PR, DIN and CEN/TC 169/WG 7, through their contact persons and at their annual meetings. In this context, the mismatch index f1' (as described above) was discussed with stakeholders during the TC 2-96 Technical Committee meeting (responsible for the revision of ISO/CIE 19476) at the Division 2 Conference in Athene, Greece, in Oct. 2022. During the runtime of the project, posters and oral presentations were also submitted and accepted for the NEWRAD conference in Sept. 2023, and the 30th CIE Quadrennial meeting in Sept. 2023.

Additionally, 4 open-access peer-reviewed papers have already been published and 3 more have been approved and submitted for publication.

Impact on industrial and other user communities

Since tungsten filament lamps were banned, LED based lighting products are the general lighting market's most rapidly evolving light sources. Test laboratories are therefore faced with a wide variety of different LED based light sources, for which reliable test results based on SI traceable measurements of photometric quantities are required to meet the demands of industry and have not yet been comprehensively developed. Standards CIE S 025/E:2015 and EN 13032-4 pave the way to improve the quality of lighting products by introducing the concepts of measurement uncertainty declarations and acceptance intervals, as mandatory requirements in test standards for LED based light sources. However, procedures to determine uncertainties especially if spectral measurements take place were missing. This project filled the missing gap and provided the appropriate procedures and the distinctive guidance necessary for a full implementation of the standards on test laboratory level.

For testing laboratories, luminance is increasing in significance for instance in relation to glare. As the use of the LED becomes ubiquitous, considerations of luminance distribution increases in significance, for instance for arrays of bright LEDs. Traceability of luminance measurements is important to gain the confidence of the market. The developed techniques and procedures were shared with industry and test laboratories at stakeholder meetings and workshops organised within this project.

To promote uptake of the project's outputs by the industrial and other communities, the project delivered the following training activities:

i) May 23-24, 2023, at PTB Braunschweig, Germany: A two-day hands-on training course on measurement with and characterisation of ILMDs. The training was attended by 28 participants from industry, universities and NMIs.

ii) July 24, 2023: A one full day online training on uncertainty determination of spectrally integrated quantities. 10 presentations on measurement uncertainty, Monte Carlo simulation, Python and Matlab implementations, the use of the projects GitHub repository and information on Basis Function technique and 2-dimensional DOE were given. In total 60 participants from industry, university, NMIs and calibration laboratories registered for this training.

iii) August 22-23, 2023, at TUBITAK, Türkiye. A two-day hands-on training on spectral measurement methods for photometric quantities. The training was attended by 23 participants from industry and NMIs. The aim of this training was to deepen the techniques presented in the online training in practice.

Participation in the training courses was advertised via EURAMET, the project website and also via the LinkedIn entries of the project partners.

Impact on the metrology and scientific communities

Since the adoption of the Guide to the Expression of Uncertainty in Measurement (GUM), the reliable determination of uncertainties is a main aspect in scientific metrology. However, in the field of testing, the use of uncertainty calculations is mostly disregarded because it is expected that any uncertainties will be covered by appropriate allowed tolerances given to the measured quantities. In many cases, this is highly justified. But in cases where the influence of details in the measurement setups on the magnitude of quantities is high, the consideration of uncertainties even in testing environments are necessary. To address this, the consortium provided a special training course (listed above in ii) where test laboratories staff was invited to give participants a deep insight not only into measurement procedures and appropriate models for the evaluation of measurement uncertainty, but also in free available software tools to establish Monte Carlo techniques that can be used in routine testing environments.

The triumph of digital cameras used for 2D-photography also paved the way for metrological cameras, so called ILMDs, used to measure 2D-distributions of light from a source or illuminated objects. This project provided calibration procedures which are published on the project website and were forwarded to the CIE so that they can be incorporated into the technical committees dealing with the revision or introduction of measurement standards. They enable fully traceable measurements in selected applications, for the first time. Thus, it fosters the entry of this innovative measuring technology into precision metrology.

CIE 198-SP2:2018 provides an analytical background for further processing of spectral data taking into account correlation. However, the analytical approach detailed here is far too complex to be useful for testing laboratories. The methods provided by this project, based on Monte Carlo simulation, are more applicable and much easier to implement with the aid of the guidelines in practical metrology that take into account the handling of correlation and metadata in future digital calibration certificates. The methods were published on the project website and made available for CIE technical committees dealing with the revision or introduction of measurement standards In addition, a procedure was made available to metrologist in photometry and radiometry to provide information about most likely impact of (hidden) correlations on the uncertainty of integral quantities derived from spectral measurements, even if no correlations are explicitly declared, e.g. based on auxiliary measurements.

Impact on relevant standards

In order to feed the work of this project into the relevant technical committees of CIE Division 2, the reportership DR 2-89 “Complementary mismatch index” was set up under the leadership of a partner of the consortium. DR 2-89 officially fed information from this project into TC 2-96 “Revision of ISO/CIE 19476:2014 “Characterisation of the performance of illuminance meters and luminance meters”, which was established in March 2021. TC 2-96 is chaired by the coordinator of this project, it currently consists of 22 members from 11 countries around the world, including 9 consortium members and 2 project collaborators. Since its establishment, 11 TC meetings were held.

In addition, another partner of this consortium, who also chaired CIE TC 2-93 on the revision of ISO 23539/CIE S 010 "Photometry- The CIE System of Physical Photometry", has also been appointed to chair the CIE TC 2-97 that works on the revision of CIE S 025. Since its establishment in April 2022, 9 TC meetings were held.

Members of the consortium and its collaborators are also involved in the following technical committees and reporterships of CIE, which deal at least in part with the topics of this project:

- CIE TC 2-93: Standard on the “Revision of ISO 23539:2005(E) / CIE S 010/E:2004 Photometry - The CIE system of physical photometry”.
- CIE TC 2-90: Report on “LED Reference Spectrum for Photometer Calibration”.
- CIE TC 2-95: Report on “Measurement of Obtrusive Light and Sky Glow”.
- CIE TC 2-62: Report on “Imaging photometer-based near-field goniophotometry”.
- CIE TC 2-86: Report on “Glare Measurement by Imaging Luminance Measurement Device (ILMD)”
- CIE TC 2-89: Report on: “Measurement of Temporal Light Modulation of Light sources and Lighting Systems”.

CIE TC 2-86: Report on Glare Measurement by Imaging Luminance Measurement Device (ILMD). As an example for ILMDs, project partners are involved in CIE TC 2-86 which is dealing with glare evaluation using ILMDs and in CIE TC 2-95 which is assembling an application list regarding measurement of obtrusive lightusing e.g. ILMDs.

As mentioned above, the international standard CIE S 025/E:2015 is up for its first revision and this project aims to increase its uptake by test laboratories by proposing revisions that will aid testing in routine test environments, thereby increasing its scope, to include commonly used methods and equipment, and improved guidance for the estimation of uncertainties for laboratories. As CEN/TC 169/WG 7 will postpone the revision of the European standard EN 13032-4, until the CIE S 025 is revised, there is a good chance that both standards will be harmonised again. Resulting from planned regular consultation and exchanges between the consortium and standards organisations CIE and CEN (via national representatives), most of the guidelines and procedures that have been developed in this project are suitable for direct use by the respective standardisation committees. In the meantime, CIE has formed TC 2-97 to revise the CIE S 025 standard, with this project specifically mentioned in the CIE Division 2 proposal as a stakeholder for TC 2-97. The chair of TC 2-97 was in turn an active member of this consortium, and other partners in the consortium have signed up for membership in the TC. In addition, the partners continued to seek memberships in other relevant technical committees established at CIE and CEN to support the publication of revised and new standards.

Some members of the American Illuminating Engineering Society (IES), responsible for the standard IES LM-79-19, are also members of the new CIE committee on the revision of the CIE S 025. So the outcomes of this project, which have been forwarded to CIE, will also have influence on the next revision of the IES LM-79.

By improving metrological transparency and trust, the project results support EU regulatory initiatives on lighting products, specifically the European Union's energy labelling and ecodesign requirements applied to lighting product, which came into force in September 2021.

Longer-term economic, social and environmental impacts

The confidence in the performance of lighting products relies on the reliability of test procedures provided by standards such as the CIE S 025/E:2015, which must cover the full spectra of product capabilities to provide reliable test results. Appropriate standards and test procedures will provide consumers and end-users with reliable information, so that they are able to choose and purchase products which best fit to their applications. Consumers will have better characterisation on which to base purchase decisions, thus helping avoid dissatisfaction and reducing unnecessary environmental waste and increasing product satisfaction in the longer term.

Using innovative instrumentation (such as ILMDs) supported by updated standards for characterisation and testing will allow more reliable and comprehensive product specifications, so that requirements for light installations due to current and future regulations can be more easily met. In the longer term, this will improve urban lighting and reduce unnecessary light emission also known as light pollution and obtrusive light.

6 List of publications

1. Kantona M., Trampert K., Schwnengel C., Krüger U., Neumann C. (2022); “Geometric system analysis of ILMD-based LID measurement systems using Monte-Carlo Simulation”; Journal of Physics: Conference series 2149; https://doi.org/10.1088/1742-6596/2149/1/012015
2. Ferrero, A., & Thorseth, A. (2021). IMPACT OF THE NORMALIZATION OF THE SPECTRAL RESPONSIVITY ON THE PERFORMANCE OF THE GENERAL V() MISMATCH INDEX, Proceedings of the Conference CIE 2021 CIE - International Commission on Illumination; https://orbit.dtu.dk/en/publications/impact-of-the-normalization-of-the-spectral-responsivity-on-the-p
3. Krüger, U., Ferrero, A., Mantela, V., Thorseth, A., Trampert, K., Pellegrino, O., & Sperling, A. (2022). Evaluation of different general V(λ) mismatch indices of photometers for LED-based light sources in general lighting applications. *Metrologia*, *59*(6), 065003. https://doi.org/10.1088/1681-7575/ac8f4d
4. Krüger, U., Ferrero, A., Thorseth, A., Mantela, V., & Sperling, A. (2023). General V(λ) mismatch index: History, current state and new ideas. *Lighting Research and Technology*, *55*(4-5), 420-432. https://doi.org/10.1177/14771535231158528

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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