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Good Practice Guide for the consideration of geometric dependencies in the determination of luminous intensity distributions and their uncertainties in goniophotometers

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19NRM02 RevStdLED

Good Practice Guide 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 (Official title)

Good Practice Guide for the consideration of geometric dependencies in the determination of luminous intensity distributions and their uncertainties in goniophotometers. (Title for publication)

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Content

Scope

This good practice guide (GPG) deals with the measurement of the luminous intensity distribution (LID) of light sources using goniophotometers and its uncertainty. The aim of classic LID measurements is usually to determine a symmetrical light distribution, whereby the specified geometry is mapped onto the main axes of the luminaire, which define the so-called (A, α), (B, β) and (C, γ) plane-systems for different angles of views [1]. The approach followed in this GPG is based on the complete description of the kinematic chain of the goniophotometer from the source to the detector and vice versa, which allows in principle the rigorous determination of uncertainties.

Motivation

Classic goniophotometers are the established systems for measuring the spatial LID of light sources in the far field of the illuminating part of the luminaire. As an innovation, imaging luminance measuring device (ILMD)-based methods have now also become established. The difference between an ILMD and a classic photometer-based system lies in the design of the detector. With classic goniophotometers, the luminous intensity is measured for one direction using a photometer measuring the illuminance at known distance from the source and which is considered to be small enough for the measurement evaluation.

The directional dependence of the luminous intensity is therefore determined by the movement of the object or the photometer in space. Goniophotometers in which the ILMD directly images the luminance of the source are known as near-field goniophotometers. The name “near-field” goniophotometer is in this respect misleading, as the total size of the luminaire may be large and with respect to the entrance optic of the ILMD in its photometric near-field. However, for the geometry of an imaged pixel, the source pixel investigated is still in far field condition. Without limiting the generality, this GPD considers classical far field goniophotometers that observes the LID with a point size receiver. This could be a photometer or a pixel of an ILMD, when the LID of the light source is measured on a reflective screen, where the screen is the effective detector plane.

Introduction

The LID $I(\varphi, \vartheta)$ is the luminous flux Φ per solid angle Ω that is emitted in the direction (φ, ϑ) [2].

$$I(\varphi, \vartheta) = \frac{\mathrm{d}\Phi(\varphi, \vartheta)}{\mathrm{d}\Omega(\varphi, \vartheta)}. \tag{1}$$

As the solid angle describes a three-dimensional opening angle that starts from a mathematical point, the necessary assumption for a light source emitting into a solid angle is that it has to be a point source, too. This indicates that the measurement distance has to be much greater than the dimensions of the device under test (DUT). The so-called photometric law of distance describes the relationship between the luminous intensity of a source in a certain direction and the illuminance generated by the source in the given direction at a certain distance. The photometric law of distance reads:

$$I = \frac{E \cdot r^2}{\cos(\varepsilon)}, \tag{2}$$

where E represents the illuminance on a photometer that is proportional to the luminous intensity by considering the measurement distance r to the power of two. The term $\cos(\varepsilon)$ defines the angle of incidence of the detector [2]. Strictly speaking, the equal sign in Eq. 2 only applies to infinite distances, since neither the source nor the detector appear to be point-shaped. Consequently, there is always a relationship between the minimum achievable error and the measuring distance specified by the measuring device.

Goniophotometer used

Although near-field goniophotometers with ILMDs are increasingly used, common methods for measuring LID are based on illuminance measurements in far-field goniophotometers, e.g. using ILMDs or photometer measurement systems [2-4]. For this, the DUT is mounted on a goniometer and illuminates the detector. In the specific case discussed here of a camera based ILMD system, the detector is a Lambertian reflecting flat white screen at a sufficient large distance to the source (see **Figure 1**). The screen represents the detector surface and an ILMD measures the luminance of the screen from which the illuminance distribution is calculated. Knowing the geometric relation between the system components, it is possible to calculate the LID in the angular range of the screen or on the photometer as the detector when the light source is rotated around its axes, respectively. However, in the setup shown in Figure 1, the reading of the calibrated photometer is "only" used to calibrate the reading of the ILMD close to the centre of the viewing range.

If the angular range of interest is larger than the screen, the recorded LID of one single measurement corresponds only to one LID-segment. To obtain the LID over any angular segment the goniometer rotates the DUT in multiple viewing directions by the horizontal and vertical axes of rotation, resulting in the coordinates (H, V). As a result, each desired direction is once seen by the screen.

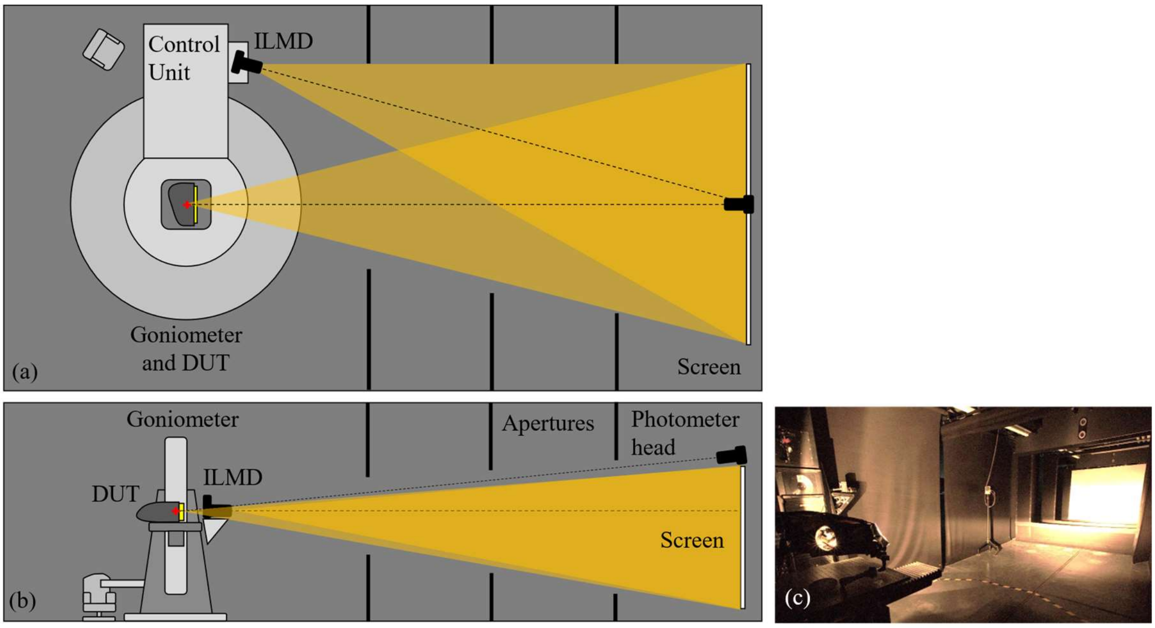

Figure 1: Scheme of an ILMD-based LID measurement system illustrated as bird view (a) and side view (b). (c) shows a photo of the measurement system measuring a car headlight.[3]

Uncertainty components

In general, there are uncertainty contributions to each LID measurement that are caused by photometric as well as geometric system components. Photometric components influence the determined photometric measurand, the illuminance E. The uncertainty components are due to e.g. stray light, non-uniformity of the screen, spectral dependencies, which includes the spectral reflectance of the screen as well as the spectral mismatch of the ILMD and photometer, respectively, and the uncertainty of the photometer measurement, which includes calibration and operation dependent uncertainties. Geometric components involve all components that influences the measurement direction (φ, ϑ) as well as the measurement distance r. These components include the spatial position and orientation of the detector (e.g. the screen), the spatial position of the goniometer, the intrinsic uncertainties of the goniometer (e.g. the goniometer-axis position accuracy during the measurement) and the position of the DUT as well as the position and uncertainty of the geometric standard used to calibrate the mechanical distances and angles. The photometric uncertainties can be determined by separate characterisation of the respective components of the setup independent of the source and the characterisation of the spectral distribution of the source. The photometric uncertainties can be determined directly using the methods described in the "Good Practice Guide on the calculation of uncertainties of integral quantities determined from correlated spectral input data" developed by 19NRM02 RevStdLED [4].

For the geometrical uncertainties, a Monte-Carlo method is used to describe how to determine the geometric uncertainty parameters following the „*Guide to the Expression of Uncertainty in Measurement*" (GUM) [5, 6]. According to the mechanical system and joints, this GPG will follow the Monte-Carlo-Method (MCM) based on an approach of B. Jokiel Jr, et al. for parallel kinematic machines [7]. A similar approach was also published already during the project by M. Katona, et al. [3] .

The advantage of the camera-based method compared to the use of a single photometer is the complete, high-resolution recording of a larger angular range at once with one image of a few million measurements. The simultaneous recording of the luminous intensity in many directions in one image generates a high geometric and temporal correlation between neighbouring directions. This wanted correlation avoids additional temporal and geometric uncertainty components and is not usable in the classic scanning method with point-shaped detectors. In practical applications, this correlation can be disturbed and may lead to significant deviations when comparing the measured luminous intensities of a specific spatial direction between the different methods or even between individual camera images for measurement objects with high gradients in the LID.

With the camera-based methods, capturing the full angular range requires a rasterization of the space and subsequent superimposition of the individual images to create an overall luminous intensity distribution for all directions. This usually results in deviations between measured values of the same spatial direction in different DUT images in the areas with superimposition. See **Figure 2**.

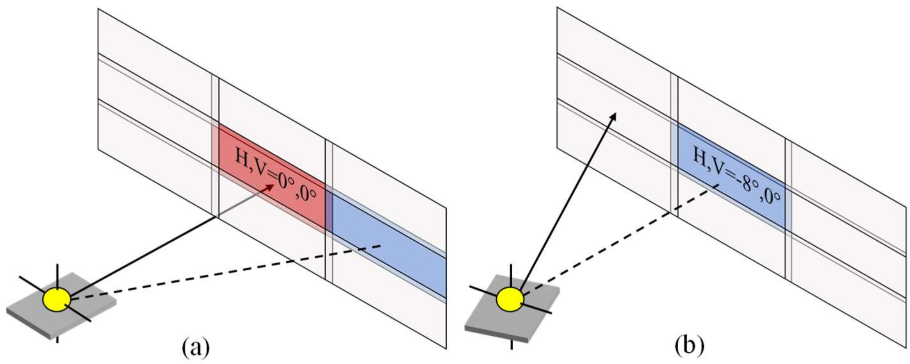

Figure 2: Schematic representation of the image stitching algorithm for composing LIDs with a larger angular range than the screen. (a) and (b) are showing two different goniometer recording positions. From [3]

These small deviations are typically not relevant in the overall measurement uncertainty budget but are very noticeable and striking due to their structure caused by the edges of the screen, shown in **Figure 3**. These anomalies in the LID of camera-based LID measurements raise the question of how to deal with these influences in the context of a measurement uncertainty determination. The main reason for these striking errors in the determination of the LID are the geometric influences on the measurement model used to determine the measurement uncertainty budget. The mathematical model required to determine the measurement uncertainty budget can be divided into a photometric, a geometric and a temporal component and their correlations with each other.

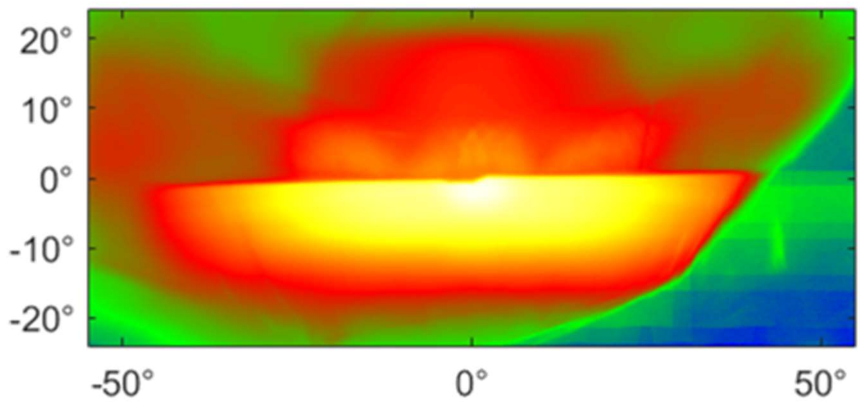

Figure 3: Image of a stitched LID with a large angular range. The characteristic steps in the measured LID resulting from edges of the screen inside the LID could be seen in the lower right corner. From [9]

The models for describing the measurement uncertainty of the luminous intensity of a source in one direction are well known and can be found in publications such as the normative document CIE 198:2011 and [4]. To determine a luminous intensity distribution, the geometric relationship of the relative individual luminous intensities to each other is of decisive relevance and the core of this guide.

The temporal component is the result of the typically necessary scanning of the angular space which is necessary for all goniophotometers. This spatial rasterization requires a certain amount of time, which depends on the path shape of the rasterization, the selected angular velocity and the angular resolution of the measurement. When determining the luminous intensity for one direction, most of the time-related influencing factors can be eliminated with a sufficiently long integration time, i.e. averaging over many modulation periods, or by setting it to an integer multiple of the modulation period. For the practical determination of luminous intensity distributions, however, a compromise must always be found between a measurement with the highest possible resolution and the fastest possible measurement, so that the integration times must be as short as possible and thus temporal modulations of the source, as well as the integration time of the measurement detector, could become relevant.

Luminous intensity distributions are as individual as their measurement objects and therefore cannot generally be described using model parameters. Luminous intensity distributions with strong symmetries can be modelled well. These are, for example, simple light sources such as classic frosted incandescent lamps or cylindrical fluorescent lamps. However, with the advent of the point-shaped LED as a light source and the improvement of the possibilities in the calculation and manufacture of freeform-optics, application-optimised luminous intensity distributions with large gradients are now possible. A well-known application example is the LID of the low beam headlight in the automotive sector, which has increasingly sharp edges and therefore larger gradients. It is important to acknowledge that luminaires involving such imaging optics in principle can create a complex characteristic of the LID (i.e. with a luminous centre of gravity that is very different for each direction) and might even involve a focussing to a location outside the luminaire rather than just divergent emission. But in the latter case, a description of the luminaire by an LID is not adequate at all, and therefore related aspects of the uncertainty, i.e. for projectors or surgical luminaires, are not covered by this GPG.

Simple luminous intensity distributions, which are typically generated with rotationally symmetrical optics such as lenses, can be modelled and approximated well with the help of $\cos^n(\alpha)$ functions. In contrast, optics with faceted reflectors may have very uneven distributions and are therefore difficult to model due to the lack of symmetries. It is therefore generally not possible to use the measured luminous intensity distribution to draw conclusions about its geometric uncertainties based on simple model assumptions.

Therefore, to determine the geometric influences on the measurement uncertainty of the luminous intensity distribution, completely closed models are always required that consider the correlation between the individual geometric variables. Here it is helpful that, from a mechanical point of view, a goniometer is a manipulator, i.e. a robot arm that holds the object in its hand. The mechanically linked axes of the goniometer can therefore be regarded as a kinematic chain. If the angle of rotation between the individual axes is known, the position of the measured object can be determined at any time using known mathematical methods from robotics. The advantage of this method is the completeness of the description and the intrinsic correlation of the variables with each other when the orientation and distance between the axes is known.

In the following, we discuss which methods and partial models are suitable for a Monte Carlo approach for analysing the geometric contributions and how these are to be set up and coupled for an LID measurement. These models can be used to determine the uncertainty of the measurement direction and the measurement distance. The advantage of the Monte Carlo approach is that the influence of the geometric uncertainty can then be coupled with the spatial characteristics of the LID, i.e. its sensitivity in the angular range, in an initial approach.

If further models are available to describe the temporal behaviour of the source, this knowledge can be coupled with the modelling of the measurement method, i.e. the temporal sequence of the rasterization of the angular range. Recommendations for modelling the measurement uncertainty of goniometric measurements.

Due to the complexity and non-linearity of the model, only the Monte Carlo simulation method is suitable here. The advantage of this method is the simultaneous calculation of all correlated and uncorrelated variables. The prerequisite for this is that the model intrinsically describes the correlation between the variables. Setting up the model is a complex task and requires a number of engineering approaches. It must be set up individually for each type of goniometer and can be reused module by module. For this reason, we can only provide information here on how to set up the model, as this Monte Carlo calculation of the model must also be implemented in the software for calculating the measurement uncertainty budget.

Geometrical description of the goniometer system

A goniometer is a mechanical manipulator and can be described very well using robotics models. The Denavit-Hartenberg (D-H) transformation method, which is a standard tool in robotics for calculating the coordinate transformation of the movement of the robot, i.e. the goniometer, is particularly suitable for this purpose. Ready-made software modules are already available for this purpose, into which only the individual parameters of the robot model need to be entered.

These models must be created individually for each type of goniometer. Using the Monte Carlo method, the measurement uncertainty can then be determined relatively easily with the software tools available today.

The description of the robot's kinematic chain is already standardised in these modules to such an extent that it can be described using the urdf file format which is a common used open source format for the description of robots. Many open source software tools such as ROS support this description and enable the modelling of the geometric behaviour not only of robots, but also of any mechanical structure with hinges and joints, as is the case with goniophotometers [8]. All that is required is knowledge of the length of the effective arms and the position of the fixed or dynamic axes of rotation between the arms. With knowledge of the rotation angles of the rotation axes and the lengths of the arms, the pose of the robot hand is known and can be calculated by simple matrix multiplications.

To determine the luminous intensity I, the distance and position between the detector coordinate system and the object coordinate system must be known in addition to the measured illuminance E at the detector. The description of the kinematic chain by the D-H matrices allows a complete description of the position of the two coordinate systems at any time, from the input window of the detector to the object and, if necessary, vice versa if the object is fixed.. This approach is published in [9].

For modelling the relative position of the detector to the object (source) in case of a static detector and a moving source (Figure 4), it is recommended to define the detector of the measuring system as the origin of the kinematic chain. The first link in the chain is then the distance between the detector and the base of the goniometer which rotates the object. The kinematic chain of the goniometer is then described from the base point via all dynamic and static axes of rotation and joints. This allows the geometric relationship between the detector and the object coordinate system, including all correlations resulting from the joints and axes of rotation, to be modelled. In case of a moving detector and static source, the kinematic chain would be defined the other way, i.e. starting at the static source.

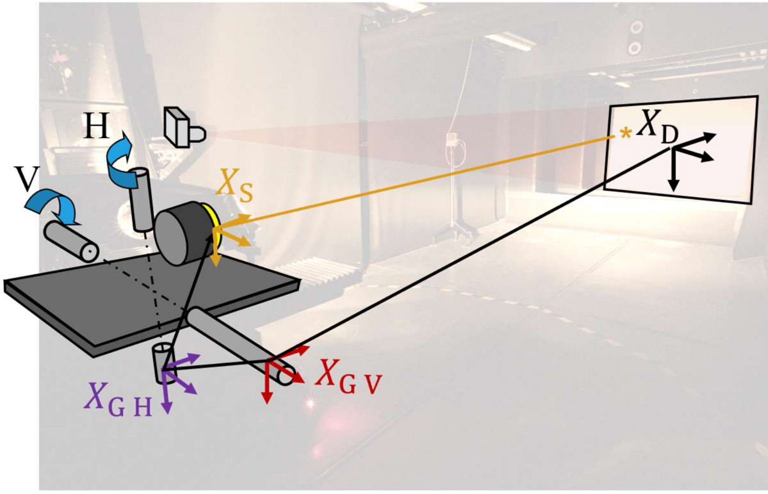

Figure 4: ILMD-based LID measuring system showing the Pose between Source S and rotation centre. From *[3]*

In our example, the last joint determines the pose between the mounting plate of the goniometer and the object coordinate system. The origin of the luminous intensity distribution is the centre of the object coordinate system. A good summary and introduction to this method can be found in the publication by Markus Katona, which was produced as part of the EMPIR project 19NMR02 “RevStdLED”. [3]

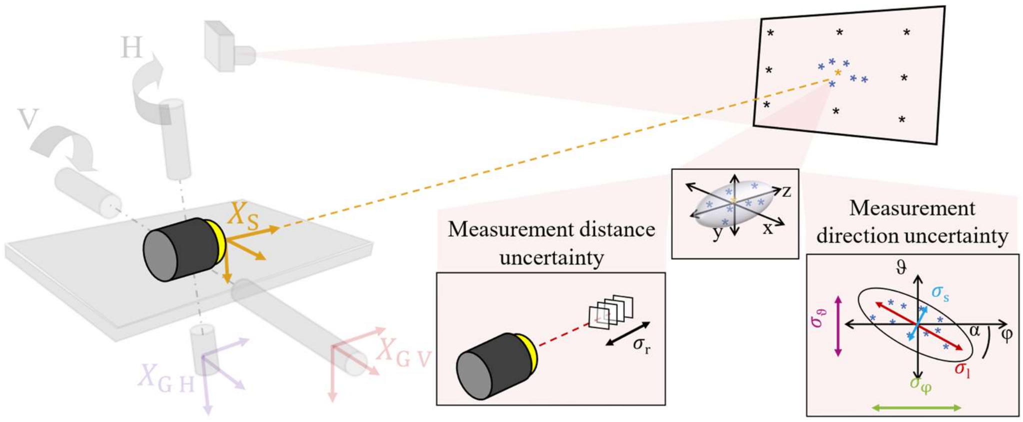

Figure 5: Geometric uncertainty evaluation for each measured direction.

Object coordinate system / luminous centre of gravity

From Katona's publication it can be concluded that for typical goniometers used as standard today, the geometric uncertainty of the machine is not the dominant contribution to the measurement uncertainty budget. The dominant contribution of geometric uncertainty in luminous intensity distributions is the unknown pose between the centre of rotation of the goniometer and the object's luminous centre of gravity. The luminous centre of gravity of the object is a mathematical model and describes the point-shaped locus that is assumed to be the origin of all luminous intensities of the object. This geometric location is necessary to be known because the luminous intensity is a vector quantity in the mathematical sense and affects the determination of luminous intensity from a measured illuminance at the detector. The origin of this vector is the luminous centre of gravity of the object and the direction of the vector is the direction of the luminous intensity in the object coordinate system. And this does not coincide with the centre of rotation of the goniometer.

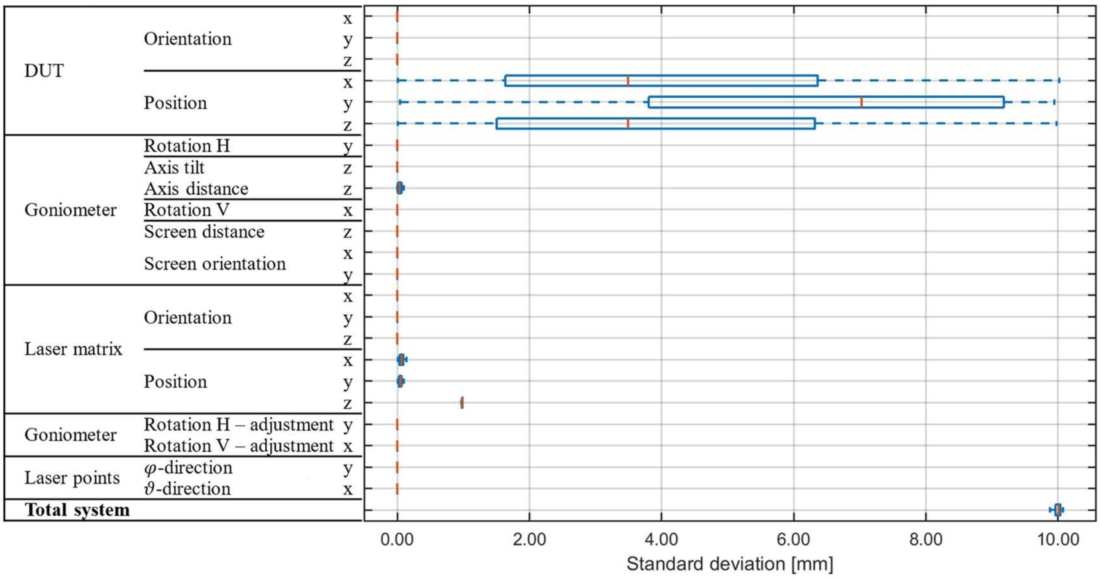

Figure 6: Example of the Uncertainty budget for the measurement distance for an ILMD LID Setup. For further explanation see [3].

The luminous centre of gravity of an object does not necessarily have anything to do with the geometric centre of the object. The luminous centre of gravity can actually only be determined from a ray data set determined by a near-field goniophotometer. Mathematically, it can be determined as the location with the smallest distance between all rays. In this case, the standard deviations of the smallest distances can directly be used to determine the uncertainty of the light centre. However, this knowledge of the position of the luminous centre of gravity in the object coordinate system is not known at the start of the far-field measurement and must therefore be assumed and determined by the operator setting up the measurement. Example of centre of gravity for luminaires are given in the standard EN 13032-1:2004+Ai 2012. If the luminous centre of gravity of an object is significantly misjudged, the resulting pose between the luminous centre of gravity of the object and the centre of rotation of the goniometer will lead to a qualitative distortion of the measured LID.

An example of this effect is shown in the following **Figure 7**. In this figure, the LID of a modelled Lambertian source with correct luminous centre of gravity is shown as a grid and the LID with misaligned COL is shown as coloured surface. The difference between these LIDs are overstated for better visibility in the figure. A description and visualisation of this effect was created by Dudzik as part of the EMPIR project 19NMR02 “RevStdLED”[10]. It is an interactive notebook for visualising and calculating the influence of the position of the centre of gravity of light when determining the LID.

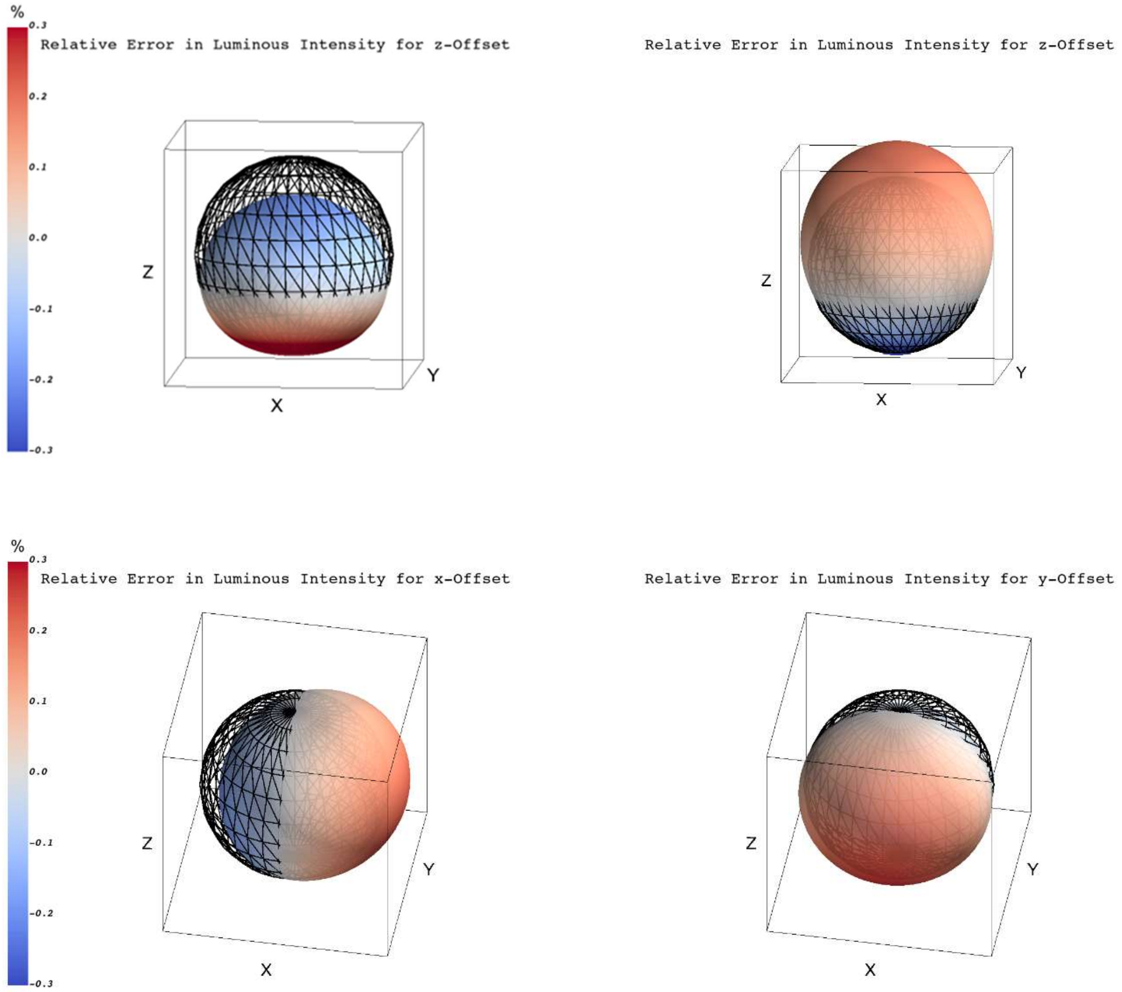

Figure 7 Influence of the pose of the luminous centre of gravity on the relative distribution of light intensity. From [10]

Experience with the quantitative description of measurement uncertainty in LID measurements

As described, it has been shown that it is possible to determine the measurement uncertainty of a luminous intensity distribution using Monte Carlo simulation. Due to the many dimensions and interdependencies, this is only possible using a simulation in a free software environment with a suitable programming language, like Phyton or ROS [8]. Due to the intrinsic correlation of the mechanical variables of the goniometer, the measurement uncertainty budget can be calculated completely using the Monte Carlo method according to GUM.

The necessary software tools are freely available on the Internet and can be used with minor adaptations. The publications mentioned above provide initial assistance for the most important modules for determining the measurement uncertainty of luminous intensity distributions.

A simple plug-and-play model cannot yet be provided due to the large number of mechanical designs used in goniometers and the large number of dependencies of the light sources on the focal position.

The general aim of a measurement uncertainty analysis is the qualitative determination of the residual uncertainty that can be assigned to the measured value with reasonable effort. In addition to the evaluation model, knowledge of the relevant influencing variables during the measurement is a necessary prerequisite for this. By listing the relevant geometric influencing variables, we would now like to provide all users with an aid that at least enables a qualitative comparison of measurements of the same object on different systems.

Relevant influencing variables

In our experience, the following influencing variables are relevant for determining the measurement uncertainty for LID measurements.

The following parameters should therefore be taken into account in a measurement uncertainty budget. Due to the complexity of the model, a purely analytical approach is associated with a disproportionately high level of effort. Existing and relevant correlations cannot be determined solely by measuring the output variable. We therefore recommend the use of a Monte Carlo simulation of the measurement. Depending on the method, the following variables must be considered and modelled.

If it is not possible to create the model and determine the measurement uncertainties, the following marginal information should at least be included in the measurement report so that a qualitative assessment of the measurement results between different laboratories is possible or the measurements are carried out under comparable conditions. The most important condition for measuring the luminous intensity distribution is the definition of the object coordinate system with the luminous centre of gravity as the centre.

- **Measuring distance**, i.e. the distance between the centre of rotation of the goniometer and the reference plane of the detector.
- **Type of goniometer**, which can best be determined using the CIE classification. The most relevant distinction for the measurement uncertainty is the influence of the measurement geometry on the operating orientation of the light source.
    - No influence: Resting focal position of the light source. In this case, the source remains stationary in space during the scan. The detector must be moved around the object. This is mainly the case with near-field goniometers.
    - Low influence: Moving source maintaining the operating orientation, i.e. the light source only rotates around a vertical axis so that the movement of the source to vary the direction of observation has no influence on the thermals inside (plasma emitter, convection) or outside (LED heat sink) the source.
    - Large influence: Moving source without maintaining the operating orientation, i.e. the source is rotated around both axes of the spherical coordinate system to change the measurement direction. The main application is in the automotive sector, as the stability of the source must be guaranteed against vibrations and changes in acceleration in the application anyway.
- **Definition of the luminous centre of gravity**
    - The centre of gravity of the light must be defined by the first laboratory, e.g. using a near-field goniophotometer. This point should be defined as precisely as possible in relation to the mechanical axes of the light source housing.
    - Photo documentation of the selected centre of rotation in all three main axes of the object coordinate system parallel to the rotation axes of the probe.
    - Selection of ONE luminous centre of gravity! Even if the measurement of the LID consists of the measurement of two half-spaces, it is essential that only one luminous centre of gravity is assumed for the object, as otherwise the results will not be

unambiguous. This is necessary because one origin is assumed when specifying a luminous intensity distribution, as the luminous intensity distribution is based on the model assumption of a point source. For better modelling, it can be useful to divide the real light source into several point light sources with different point light sources. This results in a separate LID with different centres of light for each of these sources. These LIDs can then be added together again in the application to form a resulting source, taking into account the influence of the geometry.

- **Measurement method**
  - Description of the raster method. Description of the path for rasterisation of the spherical coordinate system, which axis was moved continuously and which sequentially for rasterisation of the coordinate system.
  - Indication of whether it is a continuous movement or a start-stop operation between the individual measuring points.
- **Angular velocity**
  - The angular velocities at which the object was moved during the measurement in order to be able to calculate the resulting maximum path velocities. This allows the influence of the wind on the thermal characteristic to be estimated.
  - Determining the angular velocity is also important in order to estimate the influence of the synchronization and integration time of the measuring detector on the smoothing of gradients in angular space.
  - Determination of the integration time of the detector. With scanning systems, a long integration time of the measurement system leads to a smoothing of high gradients in the angular distribution if the angular velocity is selected too high.
- **Time behaviour of the source**
  - The time behaviour of the source has a significant influence on scanning systems, as artefacts can occur in the distribution due to the movement of the object. For this reason, it is necessary to characterise the temporal behaviour of the source as well. A distinction must be made between two different time ranges.
  - The temporal modulation of the source. This is particularly the case with sources that are operated with alternating current or with dimmed LED light sources. The output of LED light sources is usually regulated by so-called pulse width modulation. The modulation frequency is above the flicker fusion frequency of the eye and starts at frequencies from 100 Hertz. The modulation frequency must be evaluated in relation to the integration time of the detector and the angular velocity of the flicker.
  - Long-term stability of the source. Due to the rasterisation of the directions, the measurement in a goniometer usually takes several tens of minutes, during which the relative luminous flux of the source can change due to thermal drift of the source. This influence must be taken into account. The magnitude of this influence can be monitored and verified by taking two control measurements in the same direction at the beginning and end of the measurement. For an LED the electrical operation point, i.e. measurement of the voltage across the LED junction during operation at a constant electrical driving current (note: not the operation measures of an electrical ballast LED-based luminaire), is a valuable monitoring signal and typically allows a correction for fluctuation of the luminous quantity due to the operation temperature.
- **Geometric dimensions of the source**
  - The geometric dimensions of the source are usually documented. Particularly in the case of structured sources with very inhomogeneous luminance distribution on the exit surface, the luminance distribution should be assessed on this plane.

- By documenting the luminance distribution in the light emission plane, it is also possible to estimate the centre of gravity of the light much better than is the case with a purely geometric view of the light source when it is switched off.

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