19NRM02 **“RevStdLED”**

Good Practice Guide
for
Setting up an Uncertainty Budget for the Measurement of Luminance Distributions

Part 1

Estimation of Measurement Uncertainty Contributions Originating From the ILMD

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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1 Introduction

This document addresses the handling and estimation of critical measurement errors and related uncertainties that are originating from the working principle of an imaging measurement device (ILMD) and consider their relevance for selected applications. It is shown, how information from the instrument manufacturer regarding properties of his **I**maging **L**uminance, **R**adiance or **C**olour **M**easuring **D**evice (IxMD) can be used for such estimations. Further contributions related to the luminance measurement using an ILMD, i.e. mainly originating from the scene and the definition of the measurand in the application and its repeatability, are considered in a separate document (cf. Part 2 of this GPG). Both guidelines are reasonable only in case of a proper state and adequate configuration of the IMLD is ensured, which is addressed in Appendix I: Checklist for the ILMD configuration.

ILMDs are complex measurement devices based on microelectronic pixel matrix sensors as a key-enabling technology. Their complex signal path leads to multiple error sources in the optical path, the spectral weighting, the analogue signal processing and the digitalization that significantly affect the signal in an unintended way. Manufacturers design an internal model of evaluation which transforms the sensor signal with respect to internal configuration settings into a luminance signal indicated by the ILMD. Parts of these models apply corrections for relevant systematic signal distortions and therefore reduce corresponding measurement errors. However, this is increasingly problematic (also for the manufacturers) because not enough information about the pixel sensor is provided for this, and the measurement systems are becoming more complex. These models need to be parametrized by an adjustment procedure. The characterization for this adjustment is a complex task that requires a suitable setup and may take a significant amount of effort. The amount of details required depend on the number of different configurations that need to be characterized and the availability of automation.

Some of the distortions depend on internal quantities which are known (i.e. device parameters and configuration) or can be estimated during measurement. These are candidates to be corrected for. Other distortions depend on environmental condition or the scene to be measured itself, which are not known during the measurement. Here an intrinsic correction is difficult. Some corrections may be generally possible but require some computational effort. The temporal stability of the device regarding its properties is also a limiting factor for the level of detail. From these facts follows that the manufacturer has to select an internal model and the corrections to be applied that balance the effort during characterization and application and the benefit obtained. The weighting of these boundary conditions may depend on the targeted measurement task. As a consequence of this, despite internal corrections being applied, the devices will have residual systematic deviations that lead to measurement uncertainties depending namely on the extent and the quality of the internal corrections.

1.1 Aspects of Correcting for Measurement Errors

For the user there are two ways to deal with these systematic measurement errors of the readings from the device. The first is to correct for them. From the metrological standpoint this is the preferred way because the propagation of variance according to GUM requires a correction of all relevant systematic effects and propagate only stochastic components to a measurement uncertainty. This correction requires their determination and modelling by means of characteristic functions to calculate the correction for a specific measurement. Different problems come together at this task. First of all, the result depends on the internal configuration of the device and its internal adjustments. If this changes between characterization and measurement, the result may not be transferable to this new configuration. This means, the user has to make assumptions that are not based on knowledge of internal parameters. It is a contradiction to use a device just “as is", as a black-box, and then use assumptions about the internal behaviour when it seems to be useful. The second issue is that it is very challenging to stimulate the system in a way that the change of the acquired signal (luminance value) can be attributed to a specific influential quantity or mechanism. But this selective stimulation is required to determine the related characteristic without considering other mechanisms. If each influential quantity cannot be handled independently the parameter space to be scanned gets vastly large. A change of the scene/stimulus will usually affect multiple mechanisms simultaneously. If the residual systematic measurement errors are determined the uncertainty of this correction and the remaining stochastic components need to be quantified. This characterization might be possible for some devices, influential mechanisms, and measurement tasks, but it cannot be recommended as a general approach to handle measurement uncertainties.

For many users a second way to handle systematic measurement errors might be preferable. Here the systematic deviations of the readings from the device are *not corrected* but they are entirely handled as uncertainties, namely for such already corrected inside the ILMD. To determine these uncertainties, in principle one could measure a set of known luminance levels in different configurations (vary the objective lens, distance, size in the image, position in the image, integration time, ambient conditions, …) but here the same issue arises like above, i.e. the parameter space gets huge and cannot be sampled sufficiently densely. Therefore, this sampling needs to systematically cover critical measurement conditions regarding specific influential mechanisms with the goal to estimate intervals for the maximum error that can be expected from each mechanism, not to determine detailed correction functions. Because the origin of these uncertainties lies in systematic deviations, the resulting uncertainty distributions will often be asymmetric, but, resulting from missing knowledge, the underlying distributions of these errors are treated as uniform. The resulting standard deviation for an interval $[min\,..\,max]$ is then given by

$$\sigma = u = \frac{max - min}{\sqrt{12}}. \qquad (1)$$

1.2 Identification of Uncertainty Contributions

The information of what the critical conditions are is based on the knowledge of full characterizations and an understanding of the general inner working principle of an ILMD. A possible source for aspects of these characterizations is the CIE 244:2021 “Characterization of Imaging Luminance Measurement Devices (ILMDs)” [1]. The quality indices introduced there are designed to trigger different error sources and quantify the device’s performance regarding these error sources. They are designed to compare devices. The quality indexes are explicitly not usable to correct measurement results or to estimate the measurement uncertainty for a specific measurement. They also are only valid for a specific configuration. If some quality indices are provided for a device, they are not necessarily determined in a most critical configuration nor in the configuration used for a measurement. Also, not every quality index is generally relevant for the application.

This guide will select the most critical error sources that can be evaluated by the user with a reasonable amount on effort and guidance on how to estimate them. The evaluations will/may be similar to ones of the CIE 244:2021 quality indices but with variations to measure with critical configurations. For each measurement, an explanation is provided why the proposed measurement configuration is a critical one.

For effects that scale the transfer function for the pixels just by a factor, the uncertainty contributions can be expressed as a relative contribution u_{rel}. They can be transferred to absolute uncertainty contribution by just multiplying them with the output quantity Y (luminance signal) related to the pixel (or the evaluation region). For effects that are purely additive this is not helpful because the sensitivity of the output quantity to the uncertainty of the input quantity and therefore the value of the absolute uncertainty contribution u_{abs} does not just scale with the pixel signal itself. It can also depend on the signal of other pixels or on regions completely out of the measurement field (as for stray light). They have to be estimated during the measurements for the specific device configuration and scene. The overall standard uncertainty of a single luminance measurement then is given by

$$u_{\text{abs}}(Y) = \sqrt{Y^2\left(u_{\text{rel},1}^2 + u_{\text{rel},2}^2 + \cdots\right) + u_{\text{abs},1}^2 + \cdots} \quad (2)$$

All uncertainty components of a measurement Y (single pixel or evaluation region) are treated as uncorrelated, c.f. Section 9 “Correlations Between Multiple Measurements”.

The approach of not correcting for systematic effects might be not ideal in the metrological view [2], but this correction can only be done on sufficiently extensive and reliable characterization. According to VIM 2.26 [3], Measurement uncertainty is a “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”. The proposed approach works on an intentionally limited amount of “information used”.

2 Calibration Uncertainty

2.1 Technical Background

The ILMD system needs to be adjusted by the manufacturer. The determined characterization data is used to adjust the device to be able to transform the luminance at the measured scene into luminance values that are indicated by the measurement device (and taken as a reading by the operator). The complexity of this adjustment differs significantly for each ILMD model/manufacturer and its configuration, i.e. lens type. One part of this process is the “absolute calibration” to establish a link to the unit by measuring a traceable luminance standard, e.g. by the determination of a global adjustment factor and subsequent calibration of the well-adjusted ILMD. This standard itself is calibrated with a given uncertainty. Additionally, the calibration process adds uncertainties by differences between the realized measurement conditions during absolute calibration of the ILMD and the conditions with that the luminance standard was calibrated. This uncertainty of the manufacturer’s absolute calibration establishes the base uncertainty of the ILMD system.

2.2 Proposed Estimate of Uncertainty Contribution:

The information on the (relative) calibration uncertainty $u_{\text{rel,cal}}$ should be stated in the manufacturer’s calibration certificate. It might be given as an expanded uncertainty which then has to be converted to standard uncertainty. This uncertainty might be given as the uncertainty of an initial adjustment index f_{adj} from [1] which should be zero itself for an individual adjusted device.

3 Shading Error and its Focus Dependence

3.1 Technical Background

For the underlying camera system forming an ILMD the responsivity to luminance varies between the pixels. One part of this variation is the varying responsivity of each pixel of the sensor (photo response non-uniformity, PRNU) which renders in a high frequency image noise. A second part, called “shading”, is caused by the changing transmissivity of the optical path through the objective lens (lenses and aperture) and the spectral weighting filter into the pixel matrix sensor. Here the main part is caused by the varying effective/projected aperture size into the viewing direction. This effect is known as $\cos^4$-law and leads to a decline of the signal with increasing viewing angle and therefore with larger distance to the optical axis (image centre) and shorter focus lengths. A smaller contribution to the shading comes from the changing path length through the optical filters and other local variations, e.g. the pixel structure including the alignment of micro-lenses that are placed on the pixels to increase the effective light collecting area and therefore the responsivity.

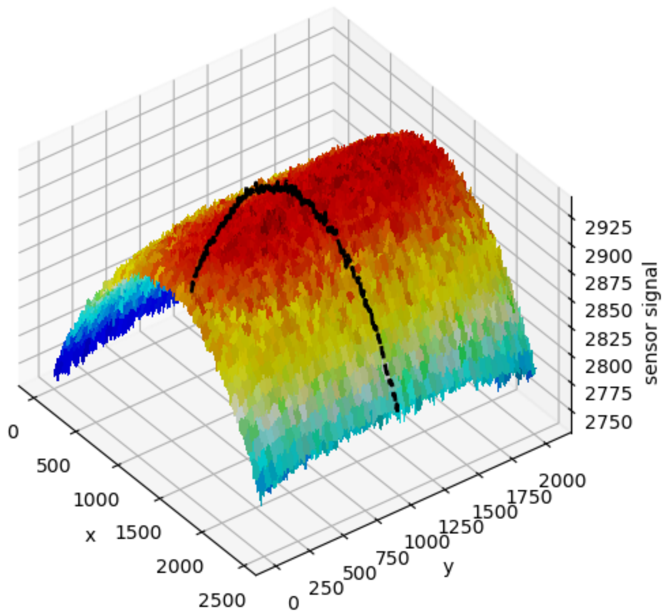

Figure 1: Example of the shading characteristic of an ILMD

To initially adjust an ILMD, the relation of the sensor signal (after some corrections) to the input luminance needs to be determined. For this one would ideally use a calibrated and homogeneous source that is extended enough to fill the whole measurement field of the ILMD. This combination is not generally available. Therefore, the adjustment gets split into the determination of the relative responsivity between the pixels and an absolute link to the SI unit for a small (usually central) pixel region (see previous section). The relative responsivity can be determined by imaging into an Ulbricht-sphere. Figure 1 shows an exemplary result of such measurement as a 3D plot. The black line shows the position of a central horizontal profile line that will be used in the next figures for better illustration. Please note that the size and the general shape of the shading effects depend strongly on the specific objective lens type and that the shown examples cannot be taken as “typical”!

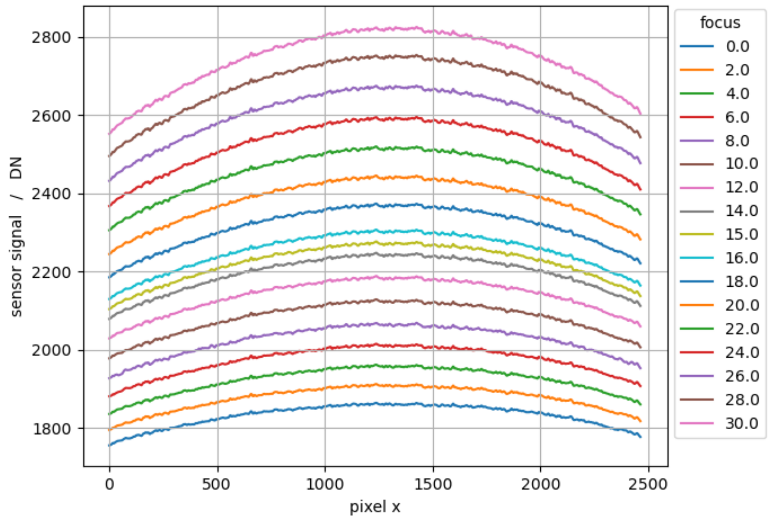

Figure 2: Focus dependence of the shading characteristic, absolute and relative

Figure 2 shows these shading profile lines for a series of measurements at different focus. It is apparent that the absolute values and the relative shapes change with the focus. For each shading dataset an average value of a small central region can be calculated as a reference value. When the shading datasets are normalized to this reference value, only the relative changes remain. Figure 3 shows the normalized profile lines where their relative change regarding to the focus gets more evident.

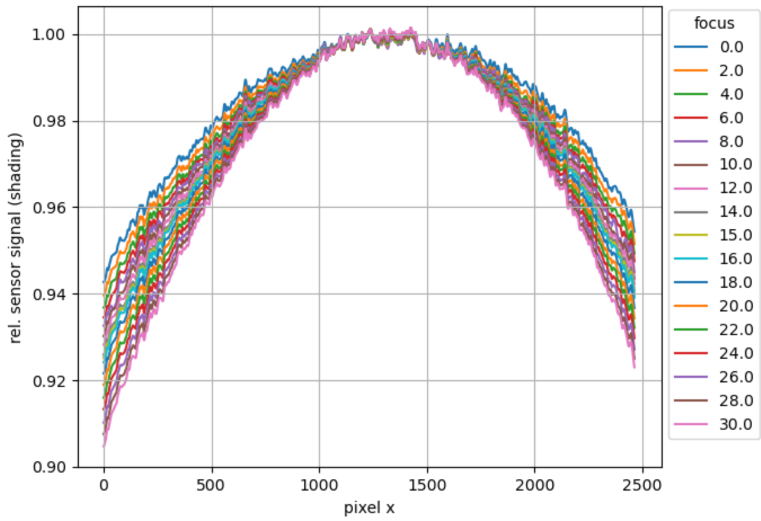

Figure 3: Focus dependency of the relative shading characteristic across the image

The reference values itself characterize the change of the absolute responsivity regarding the focus. They can get normalized themselves to the reference value of one focus setting to get a relative correction factor versus to the focus setting (Figure 4). In the ILMD control software this factor is usually implemented as a correction which value gets selected by an automated read-out or a manual selection of the current focus value of the objective lens.

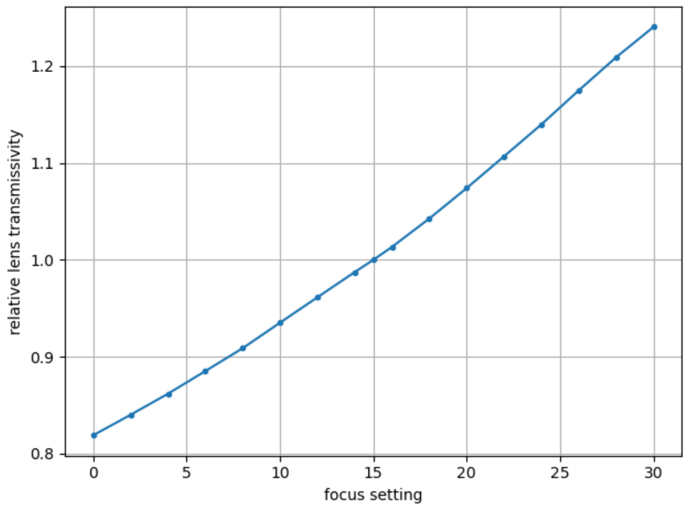

Figure 4: Relative lens transmissivity versus focus setting

Such characterization data regarding the ILMD responsivity can be used internally as an adjustment to compensate for the shading effects on a per pixel basis. Here, a balance between the effort for the characterization and handling of the data and the improvement that can be achieved is targeted. Often only one of these two-dimensional shading data sets is determined and used in combination with a global focus dependent scaling. The remaining change in the outer image regions remain as an uncertainty component.

These remaining shading errors with enabled internal correction can be determined by rotating the ILMD horizontally and vertically around its projection centre and measure the average luminance of a small homogeneous light source in different distances (small, medium, large, according to the objective's focus scale). Figure 5 shows the result of such measurements for horizontal and vertical scanning where the regions average values are normalized to the value at the image centre. With the central focus value 15 (complies to the calibration condition for this example) the shading is well compensated

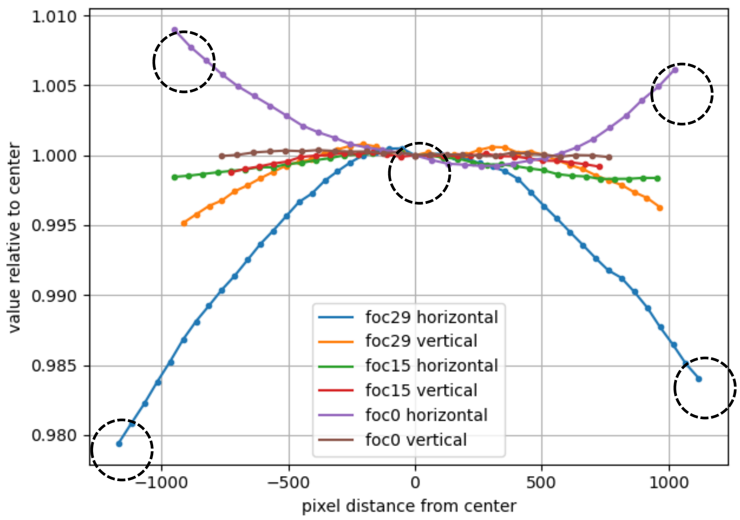

Figure 5: Relative residual shading error for different focus with respect to that at a focus value of 15

and only a very small shading error remains. With focus value 0 (small distance) the shading gets overcompensated and with focus value 29 (large distance) the shading gets undercompensated. Shading is also different in vertical and horizontal direction, and both must be investigated to properly determine the maximum shading error.

3.2 Proposed Estimate of Uncertainty Contribution:

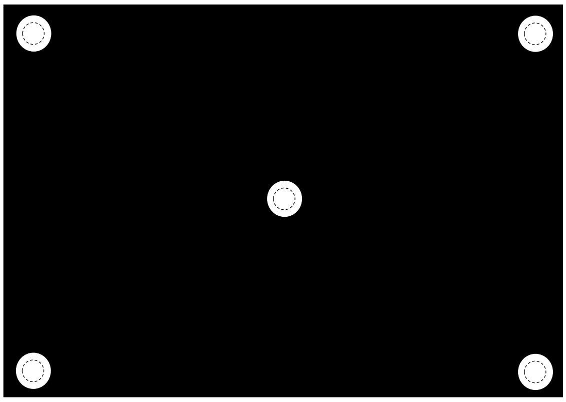

Figure 6: Measurement locations of homogenous light source by rotation around projection centre

The circular marked regions in Figure 5 correspond to the critical regions for a single axis scan. These demonstrate that the largest uncertainty contributions can be expected in the image corners. Therefore, the maximum relative errors can be estimated by, for each lens, measuring the average luminance of a small spot region in the image centre and near the image corners. Figure 6 shows these locations. The image regions should not touch the image corner. The evaluation region should be significantly smaller than the image of the source (≈50% of source).

To ensure that the source has the same luminance for all measurements, the change of the sources location in the image should be reached by rotating the ILMD (nearly) around its projection centre. This is important especially for small distances and can i.e. be realized by using a nodal point adapter for this rotation while placing the ILMD projection centre into the pivot point of the adapter to maintain the viewing position. By this the measurement direction with respect to the source is kept constant, in opposite to a translation of the ILMD. These measurements give one value for the centre Y_{centre} and multiple values Y_i for the corners (additional locations are possible). This series of single point measurements needs to be repeated for different focus settings and corresponding source distances k.

The maximum error is then given by

$$\mathrm{E}_{\mathrm{rel,shading}} = \max\left(\left|\frac{Y_{\mathrm{centre}} - Y_i}{Y_{\mathrm{centre}}}\right|_k\right) \quad (3)$$

With this the relative uncertainty follows for a uniform distribution as

$$u_{\mathrm{rel,shading}} = \frac{2\,\mathrm{E}_{\mathrm{rel,shading}}}{\sqrt{12}} = \frac{\mathrm{E}_{\mathrm{rel,shading}}}{\sqrt{3}} \quad (4)$$

In general, the distances should be varied from the lowest possible focus distance to a large one near infinity. If the adjustment distance is known, it should be used as a reference. Here the lowest residual shading error can be expected. For each distance the correct focus setting of the objective lens needs to be set in the ILMD software. It might be helpful to use additional locations on the image diagonals or the image in general (see also definition of f_{22} in [1]). This will increase the needed effort for the characterization but allows later to select appropriate subregions that correspond to a specific measurement task for the determination of $u_{\mathrm{rel,shading}}$. The same applies for the focus distances. The definition of f_{22} uses a very similar formulation to eqn. 3, but there is no requirement to determine it at different focus distances to detect the maximum values at critical focus distances. Therefore, no general recommendation can be given to use f_{22} as $\mathrm{E}_{\mathrm{rel,shading}}$. If it can be ensured that f_{22} was determined using multiple and critical focus distances, then it would be possible to use it rather than doing the characterisation on one's own.

During the variation of the distances the imaged size of the source needs to be held in a similar range to ensure that a sufficient local resolution is achieved. This can be achieved by using different sources or placing apertures in front of the source for smaller distances.

4 Non-Linearity

4.1 Technical Background

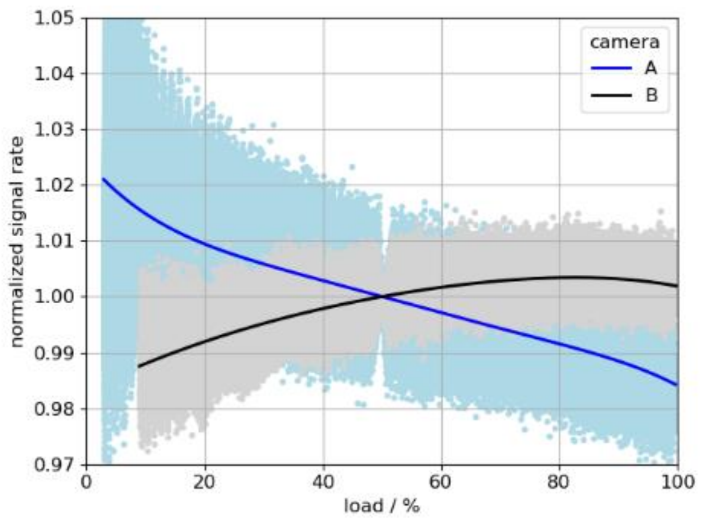

Figure 7: Examples for non-linearity characteristics

The internal components of an ILMD may show deviations from an ideal linear behaviour versus the presented luminance. This means that the respective transfer function of that component changes depending on its operating point. This operating point can usually be described by its input or output quantity. The main sources of non-linearity are the signal processing (analogue amplification and AD-conversion) and non-linear properties of the pixels photo diodes. The quantity that defines the operating point is the number of accumulated charges or, transformed by an internal gain factor, the sensors raw (count-) signal. Figure 7 shows the normalized signal rate representing the non-linearity versus the signal load of two different pixel matrix sensors that are also used in ILMDs. The non-linearity might be corrected by the device internally.

4.2 Proposed Estimate of Uncertainty Contribution:

To determine the residual non-linearity error, the average luminance of a stable homogenous light source needs to be measured while changing the internal operating point. Instead of changing the luminance level this is achieved by a variation of the integration time in multiple steps ($n_{\mathrm{ti}} = 5 \ldots 20$) to result in a signal from ≈10% load to ≈90% load of the dynamic range (available range of count values). For an ideal ILMD, the measured average luminance should be independent of the integration time. In case of a suitable internal configuration the non-linearity will not depend on the luminance level, except than for extreme low or high luminance.

To convert the averaged luminance values into a relative non-linearity, they would have to be normalized to the value corresponding to a reference point. At this reference point the non-linearity correction factor would be exactly 1. This reference point is ambiguous and the one used by the manufacturer for the internal calibration cannot be reconstructed.

A good estimation for residual non-linearity error of an ILMD is half of the range between the maximum and minimum values, normalized to the centre between maximum and minimum:

$$E_{\mathrm{rel,nl}} = \frac{(Y_{\mathrm{max}} - Y_{\mathrm{min}})/2}{(Y_{\mathrm{max}} + Y_{\mathrm{min}})/2} = \frac{Y_{\mathrm{max}} - Y_{\mathrm{min}}}{Y_{\mathrm{max}} + Y_{\mathrm{min}}} \tag{5}$$

If available, the quality index f_3 from [1] can be used as a good replacement of $E_{\mathrm{rel,nl}}$. With this the relative uncertainty follows as

$$u_{\mathrm{rel,nl}} = \frac{2\,E_{\mathrm{rel,nl}}}{\sqrt{12}} = \frac{E_{\mathrm{rel,nl}}}{\sqrt{3}} \tag{6}$$

The measurements need to be done with sufficient spatial averaging (size of the measurement region by means of number of pixels) or temporal averaging (repetitive measurements) to get stable values, not significantly influenced by photon noise. For devices with electronic shutter, the luminance should be chosen at a level that the integration time is larger than ≈10 ms. Devices with mechanical shutter might need larger integration times. This reduces the influence of the smear effect (for CCD sensors) at short integration times and the relative error on the realized integration time itself. To ensure that the result is not an issue of an integration time error, or a related internal configuration change, the measurement can be repeated using a different luminance (i.e. realized by a neutral density filter). The spectral distribution should match that of the typical objects to measure or illuminant “A” (see next section).

5 Spectral Dependence of Non-Linearity

5.1 Technical Background

As stated in the previous section the effective overall non-linearity is the superposition of different internal mechanisms. One of these is the charge generation/collection inside the pixel photodiode. The incoming light is absorbed in the silicon of the pixel with different absorption coefficient and therefore at different depths, depending on the wavelength. Blue light has only a very limited penetration depth below <1 µm but for red light it increases to some 10 µm. So, the charge generation occurs at different regions inside the pixel. During the collection of the charges the location of the internal depletion zone may move and overlap with the zone of charge generation. This leads to a reduction of the charge collection efficiency during the integration time. Despite the real non-linearity evolving during the integration time, at the end of the integration time the overall number of collected charged

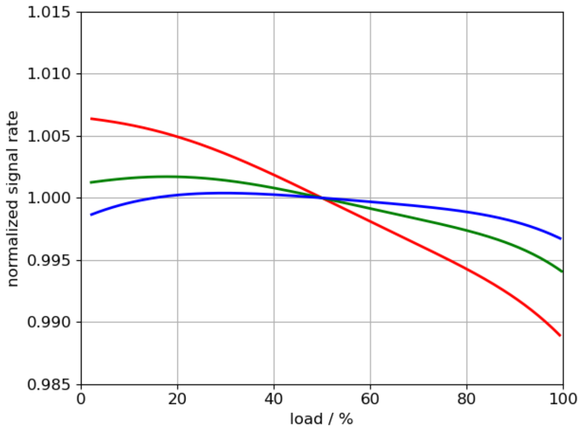

Figure 8: Example for different non-linearities for red, green and blue light

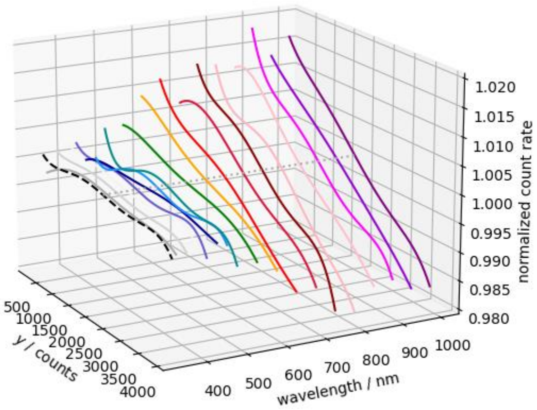

Figure 9: Wavelength dependency of the non-linearity

reduces for light with larger penetration depth (respectively wavelength), which resembles a non-linearity over the count signal [4].

Figure 8 shows an example for the effective measured non-linearities for an ILMD at the sensor's raw count signal for red, green and blue light. For blue light the non-linearity is only a few parts per thousand and thus neglectable. The non-linearity for red light is in a range from +0.7 % to -1 % and with this very similar to that measured with incandescent light. For this specific system it can be stated that most of the non-linearity is not caused by the internal signal processing but by the spectral properties of the pixel. Figure 9 shows a measurement with higher spectral resolution using a monochromator. Here is to see that up to 500 nm wavelength the non-linearity is nearly flat but above that wavelength the spectral dependency sets in and increases until 800 nm. Above that wavelength there is no further increase.

This effect is not mandatory to exist, but it may occur. This depends on the internal structure of the pixel. If an internal correction for non-linearity takes place in an ILMD, one can expect that its characteristics is usually determined with an incandescent lamp or a source similar to standard illuminant A which might have a significant spectral dependent component. Figure 10 shows an example of this effect on a device. The measured luminance values are here normalized to the value nearest to 50% load to make the characteristics easier to compare. For illuminant "A" a nearly perfect compensation can be stated, but for red and blue light, an under- and overcompensation occurs.

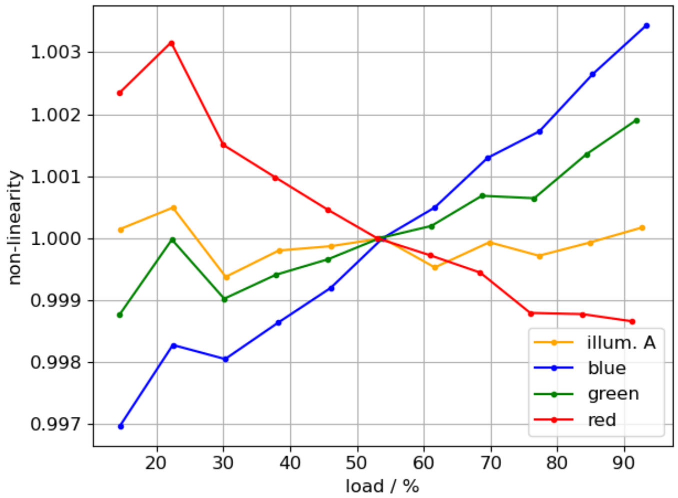

Figure 10: Residual non-linearity error for different spectral distributions

5.2 Proposed Estimate of Uncertainty Contribution:

The presence of this effect can be tested, and the resulting uncertainty contribution can be determined, by measuring the non-linearity error like in the previous section but using additionally sources with blue and red light, e.g. single colour LED-based luminance standards.

The relative uncertainty is then given as the maximum error value of all colour series k:

$$\mathrm{E}_{\mathrm{rel,nl}} = \max\left(\left.\frac{Y_{\max}-Y_{\min}}{Y_{\max}+Y_{\min}}\right|_k\right) \tag{7}$$

With this the relative uncertainty follows as

$$u_{\mathrm{rel,nl}} = \frac{2\,E_{\mathrm{rel,nl}}}{\sqrt{12}} = \frac{E_{\mathrm{rel,nl}}}{\sqrt{3}} \tag{8}$$

This replaces the uncertainty contribution of the previous section. The spectral dependency is a property of the sensor and the knowledge of the existence of a spectral dependency therefore can be transferred to other devices if their sensor type is known to be the same.

6 Size-of-Source-Effect

6.1 Technical Background

Because of diffuse scattering, optical aberrations and diffraction (described by the point spread function, PSF), parts of the light that are intended to be imaged onto a specific pixel assuming an ideal system gets instead dispersed to adjacent pixels. For larger evaluation regions that are compact (small border length in relation to the area) and relatively homogeneously illuminated these effects cancel out to a certain extend between adjacent pixels.

If the evaluation region is near the border of the illuminated region the effects gets more prominent. The effect works in both directions: dark regions surrounded by bright regions get brighter and bright regions surrounded by dark regions get darker. The overall luminous flux is constant but the distribution in the image differs from an ideal imaging.

Figure 11: Photo of an iris in front of a light source used to illustrate the size-of-source effect

To demonstrate and estimate the significance of this effect an iris is to be placed in front of a homogeneous illuminated surface (Figure 11). The ILMD is focused to the aperture of the iris. Then the iris is closed to minimum aperture, so that the aperture's size in the image is just one pixel (Figure 13, left). A measurement line through this central pixel is defined, wide enough to cover the full diameter of the

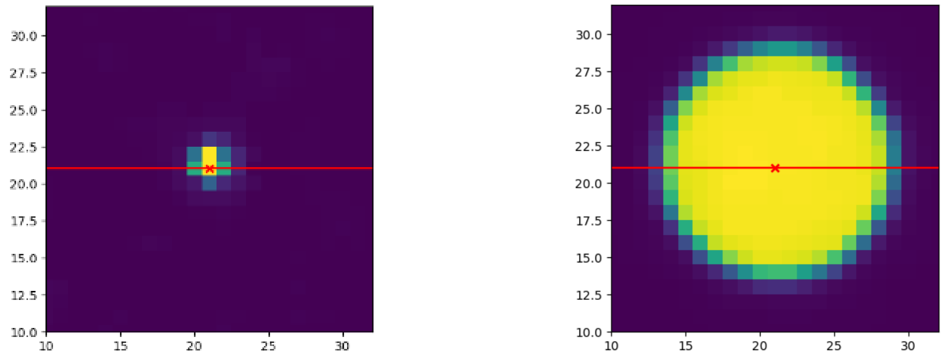

Figure 13: profile line through measurement region of variable aperture
left: smallest possible iris size ≈1 pixel, right: largest possible iris size

open iris (Figure 13, right). Then a series of measurements with increasing iris diameter is done and the line profiles are plotted, normalized to the maximum value of all profile lines at the central pixel.

In the example images of Figure 12 the width of the edge appears to be about three pixels wide. One might expect that for an iris diameter larger than twice the border width the central pixel's value keeps constant with increasing iris diameter and inner region show a plateau, because of the homogenous background luminance. But this is not the case and the establishment of a plateau requires in this example a source diameter (full width at half maximum in the image) of at least 15 pixels (iris diameter 7.0 mm, red line). Taking into account that two to three pixels are needed to define a flat plateau at the top, one ends up with an edge width of about five to six pixels. This defines the minimum distance, for this sensor/lens combination, that the evaluation region needs to have from strong gradients. If the imaged size of the source gets smaller, the measured value in the centre drops down rapidly (iris diameter <= 5 mm). A consequence from this is, that this effect cannot be handled as an uncertainty, and that *it is not reasonable to measure average luminances of sources with only a few pixels in size*! Despite that it might be common to gain geometrical information on the scene (e.g. angles between light sources) and luminance measurements out of the same image, this might lead to large errors if the source sizes in the image are too small. A better strategy here is to change the lens between wide angle lens for the geometrical information and an appropriate tele lens for the luminance measurements.

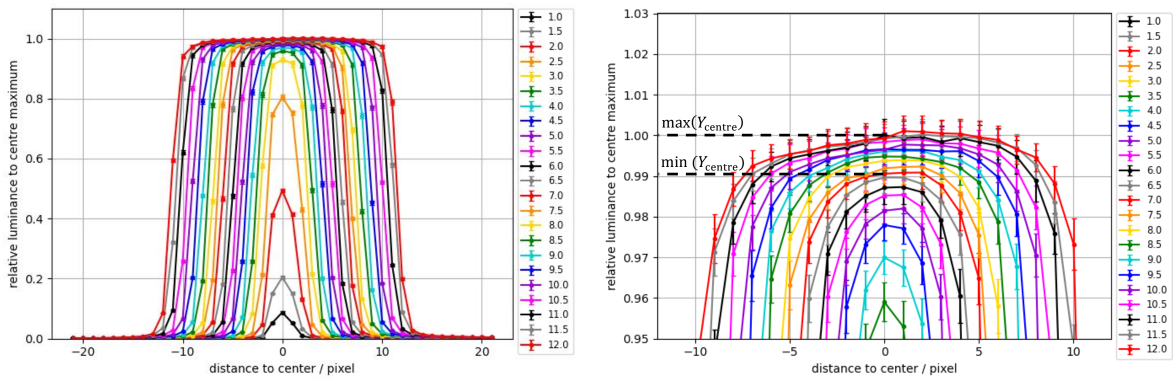

Figure 12: Measured profiles for different iris diameters, left: full profile, right: zoomed in

The second aspect that can be seen in Figure 12 is that the central value further increases for iris diameters larger than 7 mm where the plateau evolved. The increment gets smaller with the iris diameter but to reach limit value the diameter needs to be very large. The correct value lies in this range and depends on the device's calibration conditions. This can be handled as an uncertainty component.

6.2 Proposed Estimate of Uncertainty Contribution:

A measurement like shown before should be done with a reduced set of apertures. The apertures can be realized by an iris or a few fixed apertures. The goal is *not* to measure a full series like shown in Figure 12 but to determine two parameters:

1. The lower size limit where for a homogenous source a plateau gets established. This is to estimate the minimum distance of the evaluation region to the source border.
2. The relative change of that centre value between that lower size limit and a maximum source size (up to full measurement field).

The iris is usually required to realize diameters down to 1 mm. Depending on the measurement field of the ILMD, the distance has to be adjusted to realize image sizes of the aperture in the range of a few pixels. For this test only the central pixel or at maximum a region of 3 by 3 pixels is measured. Therefore, a sufficient temporal averaging is required to reduce the influence of the photon noise (n = 100). Appropriate baffles have to be used to ensure that no light that passes the iris at the outside should hit the lens. It is recommended for this characterization to check and remove any post-processing from the software if activated such as smoothening, averaging, spike elimination etc.

The maximum source size can be simply realized by removing the iris and baffles. The size of the light source should fit the maximum size expected to be measured (regarding the imaged size). Diffuse LED panels might be suitable if their LEDs are operated by a direct current (i.e. no PWM). A sufficient homogeneity is only required for the central region to be measured, not for the whole source. The source should not be directly behind the iris to prevent backlash from the iris to the source that would change the luminance of the measured central pixel/region. This distance also improves the homogeneity by putting the source out of focus. The point spread function might broaden towards the edges/corners of the image. The size-of-source effect might change/increase at outer image locations. Therefore, this characterization might be repeated with imaging the aperture at a corner.

The relative maximum error is then given by half the ratio of the span to the mean value:

$$E_{\mathrm{rel,sos}} = \frac{\max(Y_{\mathrm{centre}}) - \min(Y_{\mathrm{centre}})}{\max(Y_{\mathrm{centre}}) + \min(Y_{\mathrm{centre}})} \tag{9}$$

This leads to the relative uncertainty

$$u_{\mathrm{rel,nl}} = \frac{2\, E_{\mathrm{rel,sos}}}{\sqrt{12}} = \frac{E_{\mathrm{rel,sos}}}{\sqrt{3}} \tag{10}$$

For the shown example this gives a $E_{\mathrm{rel,sos}}$ of ± 0.5% for region sizes between 15 (iris 7) and 22 (iris 12) pixels (ignoring the fact that the upper limit is defined by the maximum iris diameter, which is much smaller than the measurement field). This leads to an $u_{\mathrm{rel,nl}}$ of 0.29%.

7 Straylight into Dark Regions

7.1 Technical Background

The Size-of-Source effect of the previous section was induced by straylight from surrounding bright regions into the *bright* evaluation region of the same source. In the same way light might get dispersed from bright regions into neighbouring regions of lower luminance. This is usually a smaller absolute error than in the size-of source effect, but it gets relevant when measuring background luminances in a scene with large bright sources.

7.2 Proposed Estimate of Uncertainty Contribution:

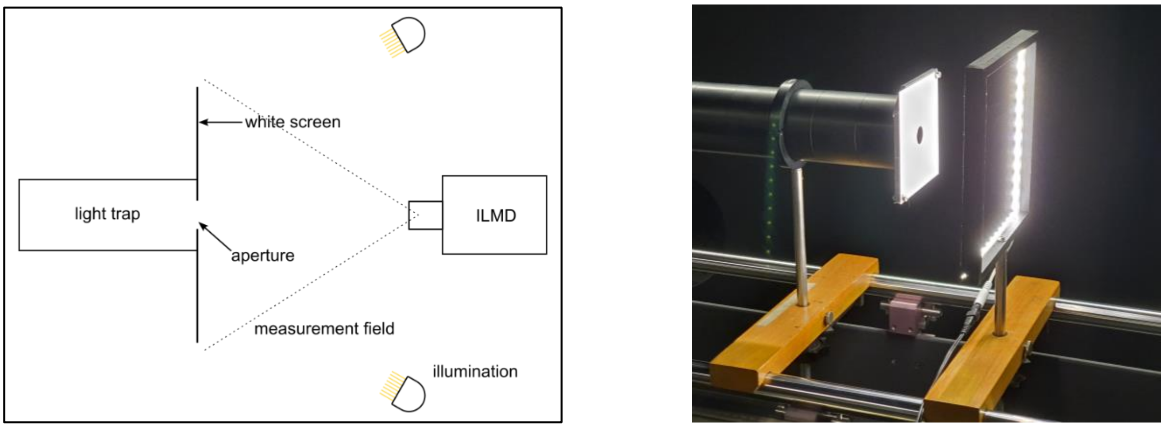

Figure 14: Measurement of negative contrast; left: sketch of setup, right: example setup

For ILMDs without internal straylight correction, an approach to estimate the straylight from surrounding bright regions into dark evaluation regions is to determine the negative contrast by measuring the average luminance in a light trap (Y_{trap}) and the surrounding relatively homogeneous large bright white area (Y_{bright}), similar to quality index f_{24} of [1]. Figure 14 shows a sketch and a realisation of the measurement setup and Figure 15 depicts the evaluation regions.

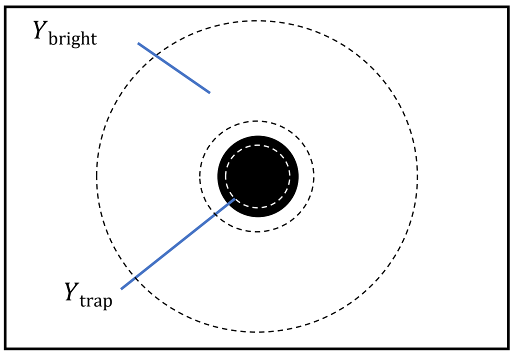

Figure 15: Measurement of negative contrast, defining evaluation regions

The luminance ratio $\frac{Y_{\text{trap}}}{Y_{\text{bright}}}$ describes the negative contrast for this extreme case where large portions of the imaged scene are bright illuminated and generate straylight into the small dark region. If the quality index f_{24} is available for the device, it can be directly used as this luminance ratio.

This device property can be used to scale a surrounding luminance of another scene for estimating its resulting absolute straylight contribution:

$$\mathrm{L}_{\text{abs,stray}} = \frac{Y_{\text{trap}}}{Y_{\text{bright}}} Y_{\text{surround}} \tag{11}$$

Strictly speaking, Y_{surround} would be the average luminance outside of the dark evaluation region but it can be approximated by the average luminance of the whole image. $\mathrm{L}_{\text{abs,stray}}$ is the estimated straylight "floor" for the whole image.

This gives the resulting absolute uncertainty as:

$$u_{\text{abs,stray}} = \frac{2\,\mathrm{L}_{\text{abs,stray}}}{\sqrt{12}} = \frac{\mathrm{L}_{\text{abs,stray}}}{\sqrt{3}} \tag{12}$$

8 Focus-Setting

8.1 Technical Background

As shown in Figure 4, the optical transmissivity of the lens may change with the focus setting. The overall change of this transmissivity can be from some ten percent down to a few percent. The lens focus is usually adopted so that the detail to be measured is in focus and therefore arbitrary, except for special cases. Depending on the lens properties the focus setting of the lens can be read out electronically or has to be entered by the user into the ILMD software. For manual input the focus setting has to be read by the user from a scale at the lens.

Here we assume that the focus scale divides the total angular range of the focus ring evenly into small steps and allows a numerical reading. Scales that display the focus distance are strongly non-linear and usually made for informational purposes, not for precise reading of the setting. Because the focus rings of the lenses usually do not provide vernier scales, the error of this focus reading E_f will be above ±0.2 step. The ILMD software may only allow the input or selection of integer focus values which increases the possible error of the focus value parameter inside the ILMD software to ±0.5 steps with a uniform distribution.

This uncertainty of the focus value parameter available to the ILMD translates into an uncertainty of the internal focus correction and therefore of the measured luminances.

8.2 Proposed estimate of uncertainty contribution:

In case the manufacturer provides values for the relative transmissivity or their inverse as a corresponding correction factor, then they can be used to determine the delta of the focus correction per focus step. If this data is not provided, it can be estimated by measure a constant source and vary the focus setting in the ILMD software. What usually would be an error when operating the ILMD is done intentionally to reveal the range of the internal focus correction. The change in the measured values is directly proportional to the change of the internal focus correction factor.

To do this estimation the following steps are necessary:

- Place the ILMD in front of an extended light source that is constant during the measurement. Homogeneity and focusing are not relevant here.
- Define an evaluation region, sufficiently large to reduce influence of photon noise.
- Measure the average luminance Y in that region for at least minimum and maximum focus setting $(f_\mathrm{min}, f_\mathrm{max})$. Some additional measurements at intermediate focus settings might be helpful to verify the absence of a strongly non-linear dependence.
- Normalize the difference of the measured luminance values to their average. This gives the relative change of

$$\Delta_\mathrm{rel,Y} = \frac{Y(f_\mathrm{max}) - Y(f_\mathrm{min})}{\bar{Y}} \tag{13}$$

The resulting uncertainty of the focus correction and therefore of the measured luminance is then given by

$$u_\mathrm{rel,foc} = \frac{E_\mathrm{f}}{\sqrt{3}} \frac{\Delta_\mathrm{rel,Y}}{f_\mathrm{max} - f_\mathrm{min}} \tag{14}$$

Figure 16 shows two examples of these measurements for two lenses with different amount of the change of relative transmissivity. To make the characteristics comparable to the device data provided by the manufacturer, the luminance values are normalized to a focus setting at device calibration, not the average value. It is evident, that the estimated characteristics match the calibration date very well.

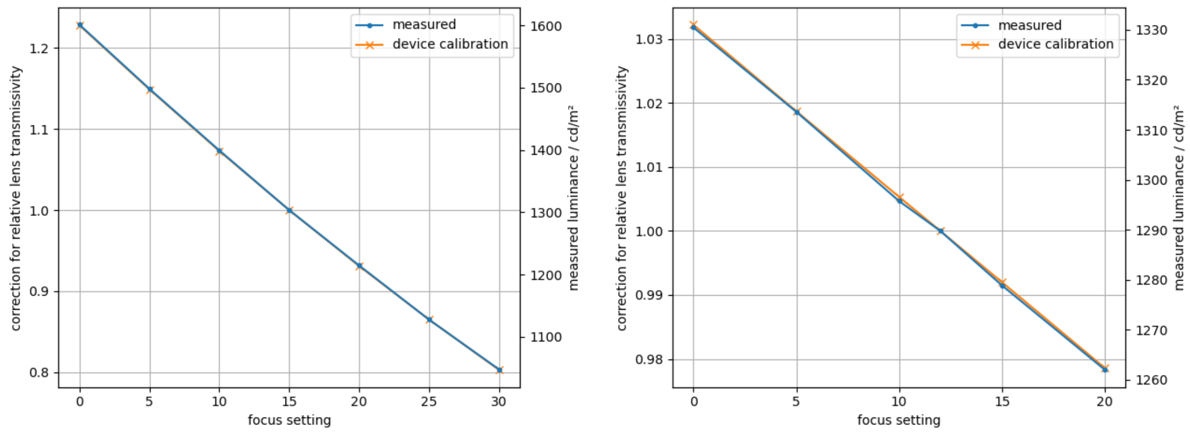

Figure 16: Examples for lens transmissivity for two lenses; estimated by changing the internal focus setting for a constant lens/scene setting compared with manufacturer-provided device data for comparison

For an expected maximum error of the focus reading of $E_{\mathrm{f}} = 0.5$ we get for the left example with a relatively large focus dependency and using measured luminance values or correction data:

$$u_{\mathrm{rel,foc}} = \frac{0.5}{\sqrt{3}} \cdot \frac{1601 - 1047}{1601 + 1047} \cdot \frac{2}{30} = \frac{0.5}{\sqrt{3}} \cdot \frac{1.2285 - 0.8035}{1.2285 + 0.8035} \cdot \frac{2}{30} = 0.0040 \tag{15}$$

For the right example we get:

$$u_{\mathrm{rel,foc}} = \frac{0.5}{\sqrt{3}} \cdot \frac{1331 - 1262}{1331 + 1262} \cdot \frac{2}{20} = \frac{0.5}{\sqrt{3}} \cdot \frac{1.0320 - 0.9785}{1.0320 + 0.9785} \cdot \frac{2}{20} = 0.00077 \tag{16}$$

which is neglectable in most cases.

9 Other Uncertainty Contributions

The shown uncertainty contributions in the sections before are a selection of prevalent contributions that can be estimated by the user of an ILMD with reasonable amount of effort. One generally relevant contribution is the spectral mismatch but the determination of the normalized spectral responsivity of an ILMD requires specialized complex setups that are not commonly available/affordable. Therefore, for the spectral responsivity the user usually has to rely on data provided the manufacturer or other laboratories. With this and knowledge about the source spectrum it is possible to determine the spectral mismatch and handle this as an uncertainty, like in this document, or to correct for and then needs to state the residual uncertainty.

Other contributions that might be relevant for a specific device, relate to the mechanical stability of the ILMD or the repeatability of settings like aperture repeatability (f_{28}) or shutter repeatability (f_{27}) for mechanical shutters. These indices describe the relative spread of the reading caused by the respective influence and can be used directly as $u_{*,\mathrm{rel}}$ or easily determined according to [1].

Dark signal might get relevant if very long integration times are used. But modern devices implement a sufficient internal correction or allow to measure correction data that fits the current temperature state of the device to a correction. Therefore, this will only be relevant for special applications. Quantisation errors can be considered as neglectable for modern devices.

If some contributions are suspected as relevant, then the task is to find the interval limits of the output signal Y and relate it to a reference point, e.g. the centre of the interval, like shown for the selected contributions before.

10 Correlations Between Multiple Measurements

In the introduction was stated that no correlations between uncertainty components for a single luminance measurement Y are regarded. This was required because the complexity of their determination is the same as the determination of the correction functions, in addition the underlaying mechanisms are quite independent and therefore their residual errors are assumed to be uncorrelated to another. But for multiple luminance measurements with the same device the same errors occur in each of them and statements on full correlations between some uncertainty components of these measurements can be made.

For a single luminance measurement, the measurement value L is given by the model of evaluation

$$L = Y \cdot c_{\mathrm{a}} \cdot c_{\mathrm{b}} \cdot \ldots \tag{17}$$

where

Y: devices luminance reading

$c_{\mathrm{a}}, c_{\mathrm{b}}, \ldots$: correction factors for uncertainty components, all $c_i \equiv 1$ (no correction applied) but with assigned uncertainty $u_a, u_b, \ldots$

When derived quantities have to be calculated from multiple luminance measurements, e.g. a luminance ratio or a difference of luminance values, the model of evaluation is given by the equation of this derived quantity, e.g. for the luminance ratio:

$$R_{L_1,L_2} = \frac{L_1}{L_2} = \frac{Y_1 \cdot c_{\mathrm{a},1} \cdot c_{\mathrm{b},1} \cdot \ldots}{Y_2 \cdot c_{\mathrm{a},2} \cdot c_{\mathrm{b},2} \cdot \ldots} \tag{18}$$

or the luminance difference:

$$D_L = L_1 - L_2 = Y_1 \cdot c_{\mathrm{a},1} \cdot c_{\mathrm{b},1} \cdot \ldots - Y_2 \cdot c_{\mathrm{a},2} \cdot c_{\mathrm{b},2} \cdot \ldots \tag{19}$$

If the critical measurement conditions at the individual measurements are the same, then the corresponding uncertainty components $u_{*,1|2\ldots}$ are fully correlated. For example, the calibration uncertainty u_{cal} is for all measurements with the same device fully correlated. If the measurement regions for successive measurements are identical or at a very similar region of the image and the focus setting is identical, then the uncertainty contribution caused by the shading error is fully correlated. For measurement regions near the image centre this is also valid for different focus settings. Measurement regions in different parts of the image have to be treated as uncorrelated regarding the shading error.

Partial correlations cannot be derived by this analytical method. This would require detailed determination on the systematic residual errors. But from the knowledge which critical measurement conditions are identical between different evaluation regions in one or multiple luminance images taken, a correlation matrix can be created to hold the correlation information in a standardized way.

To give an example, assuming a measurement of the average luminance of two different sources of the same type in one image, one evaluation region in the centre and one near the corner. As significant uncertainty components were calibration uncertainty $u_{\mathrm{rel,cal}} = u_{\mathrm{a}}$, residual shading uncertainty $u_{\mathrm{rel,shading}} = u_{\mathrm{b}}$ and a residual spectral nonlinearity $u_{\mathrm{rel,nl}} = u_{\mathrm{c}}$ identified. Because both measurements are done with the same device, $u_{\mathrm{a},1}$ and $u_{\mathrm{a},2}$ are fully correlated. Both measurements are done at different positions in the image, there is no full correlation for the shading errors and we take these as uncorrelated to another. Both sources are the same type and therefore have the same spectral distribution and a similar luminance. Therefore, the sensor will give similar count signal for both regions. With this follows that $u_{\mathrm{c},1}$ and $u_{\mathrm{c},2}$ are fully correlated. This information can be put into a correlation matrix $\mathbf{P}$ by setting the corresponding non-diagonal elements to 1:

$$\mathbf{P} = \begin{array}{c} \\ u_{\mathrm{a},1} \\ u_{\mathrm{b},1} \\ u_{\mathrm{c},1} \\ u_{\mathrm{a},2} \\ u_{\mathrm{b},2} \\ u_{\mathrm{c},2} \end{array} \begin{array}{c} \begin{array}{cccccc} u_{\mathrm{a},1} & u_{\mathrm{b},1} & u_{\mathrm{c},1} & u_{\mathrm{a},2} & u_{\mathrm{b},2} & u_{\mathrm{c},2} \end{array} \\ \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \end{array} \qquad (20)$$

(coloured elements are row/column-captions, not matrix content)

With the diagonal matrix of the input uncertainties

$$\mathbf{D} = \mathrm{diag}(u_{\mathrm{a},1}, u_{\mathrm{b},1}, u_{\mathrm{c},1}, u_{\mathrm{a},2}, u_{\mathrm{b},2}, u_{\mathrm{c},2}) = \begin{bmatrix} u_{\mathrm{a},1} & 0 & 0 & 0 & 0 & 0 \\ 0 & u_{\mathrm{b},1} & 0 & 0 & 0 & 0 \\ 0 & 0 & u_{\mathrm{c},1} & 0 & 0 & 0 \\ 0 & 0 & 0 & u_{\mathrm{a},2} & 0 & 0 \\ 0 & 0 & 0 & 0 & u_{\mathrm{b},2} & 0 \\ 0 & 0 & 0 & 0 & 0 & u_{\mathrm{c},2} \end{bmatrix} \qquad (21)$$

the covariance matrix $\mathbf{\Sigma}$ is then given by

$$\mathbf{\Sigma} = \mathbf{D}\,\mathbf{P}\,\mathbf{D}$$

This matrix then can be used for uncertainty propagation according to GUM [5]–[7].

11 Relevance of Different Uncertainty Contributions for Exemplary Measurement Applications

From the technical background of the discussed uncertainty sources some criteria can be derived, which one are possibly relevant for a specific measurement application. These criteria focus on single luminance measurement values. Some uncertainty contributions for single measurement may cancel out at the calculated final quantity because of correlations but this is not addressed here.

Absolute Calibration: This has the same importance for all applications.

Focus Setting: This has the same importance for all applications.

Shading: Are evaluation regions located in outer image regions or near centre? For outer regions the shading gets relevant.

Non-Linearity: Are absolute values measured or are evaluation regions with different luminance in same image used? Then non-linearity is relevant.

Spectral Non-Linearity: Sources to be measured have different spectral distributions vs. illuminant A (or similar). Esp. for narrow banded coloured sources spectral-non-linearity can be relevant.

Edge Distance: Allows the size of the source in the image to define an evaluation region that is kept away of strong gradients (edges) or is large enough that the edge region is small compared to the entire area. Of not, this is relevant. This is not an uncertainty component but an evaluation condition that has to be met.

Size-of-Source: What is the ratio of the measurement region to the surrounding source between different evaluation regions? What is the ratio of the measurement region to the surrounding source compared to the calibration condition? If absolute values are measured, this is relevant. If the ratio is changing, this effect might be not relevant for derived quantities because of correlations.

Negative Contrast: If measurements in dark regions are done while bright sources are present in image, then this is relevant.

The following section will give some examples for the application of these criteria to real measurement tasks, by applying them to the applications collected in section 14 (“Appendix II: List of Measurement Applications”).

Laboratory – Uniformity of Sources:

Analysis of uniformity of laboratory luminous sources for calibration at different luminance levels.

- High contrast at source border → edge distance relevant
- Source fills measurement field (vertical) → shading relevant
- Varying size of evaluation regions → size-of-source relevant

- All measurements at similar luminance → for the calculated luminance ratio non-linearity not relevant because of full correlation
- No measurements in dark regions → negative contrast not relevant

Advertising – Luminous Signal:

Measurement of luminance and analysis of uniformity on dynamic luminous signals used in advertising:

- The whole measurement field is used → shading is relevant
- Absolute values are measured → non-linearity relevant
- No strong gradients → edge distance not relevant
- No measurements in dark regions → negative contrast not relevant
- Temporal Light Modulation (TLM) may be relevant (not covered in this document)!

BlackMURA:

Evaluation of the uniformity of displays especially for the dark state. Relative measurements of lowest/highest luminance in image of display:

- The whole image is evaluated → shading across the measurement field is relevant
- Different luminance levels in one image, depend on the inhomogeneity of the DUT → non-linearity is probably relevant
- No small sources or strong gradients → edge distance is not critical
- Broad spectra → spectral non-linearity not relevant

TI (Threshold Increment):

- Measurements of multiple sources (evaluation regions) distributed across the measurement field → shading is relevant
- Measurement of bright and dark sources → non-linearity and straylight (negative contrast) are relevant

L20-Measure:

Measuring luminance values of road surface on tunnel entrance under fixed viewing position for specific viewing direction.

- Measure mostly in the centre → shading not relevant
- Bright and dark regions → non-linearity and negative contrast relevant

UGR-Measurement:

Measurement of background luminance and luminance produced by each luminaire.

- Full measurement field used → shading relevant
- Dark and bright regions measured → non-linearity and negative contrast relevant
- If no coloured sources measured → spectral non-linearity not relevant
- Small sources → edge distance relevant, size-of-source relevant

Luminance Measurements in Tunnels:

Measuring luminance of road surface**.**

- Large measurement field used → shading relevant

- Absolute values required → non-linearity relevant
- Measurement in areas with low gradient → edge distance not relevant

Street Lighting EN13201 Measuring grid:

Measuring luminance of road surface under fixed viewing conditions for specific point grid raster.

- Measurement of street surface, bright luminaires in image → negative contrast relevant
- Evaluation region only near image centre → shading not relevant
- Absolute values required → non-linearity relevant
- No coloured sources → spectral non-linearity not relevant

Photobiological safety:

Dimensional measurement of the luminous area with emission above 50% of maximum.

- Neutral-density filter might change shading → shading relevant
- White or colour LED → spectral non-linearity relevant
- No measurement in dark regions → negative contrast not relevant

12 References

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[7] BIPM *et al.*, 'Evaluation of measurement data — Supplement 1 to the "Guide to the expression of uncertainty in measurement" — Propagation of distributions using a Monte Carlo method'. [Online]. Available: https://www.bipm.org/documents/20126/2071204/JCGM_101_2008_E.pdf/325dcaad-c15a-407c-1105-8b7f322d651c

13 Appendix I: Checklist for the ILMD configuration

To avoid significant errors which cannot be covered by uncertainties it is necessary to use a configuration that is suitable for the application. Namely the following aspects should be ensured:

Good state of device components

- correct assembly and professional handling, i.e. clean and not damaged
- documentation of usage and relevant aspects of storage/transport
- consider using clean room gloves when handling optical surfaces and blow dust away by N_2 or oil free air

Selection of an adequate objective lens

- focal length → resulting in a measurement field that is fitting to the application, i.e. a focal length as large as possible.

Selection of an adequate neutral-density filter

- to avoid extremely short integration times where the timing uncertainty gets relevant
- to avoid/reduce effects of Temporal Light Modulation (TLM)

Setting of utilized optical components into the control software

- i.e. type and serial number of the objective lens, neutral density filter. This is relevant also for relative measurements inside the image, it might reset to default after start-up.

Adjustment data loaded into the control software

- configuration file, calibration file for internal corrections, user defined corrections belonging to the actual condition (consider aging and replacement/maintenance of components since the characterization)

Stabilized internal temperature for all components

- i.e. ILMD in operation (powered up and initialized, i.e. imaging loop) for more than one hour

Dark signal correction inside the control software

- belonging to the operation mode (i.e. binning, smoothing, integration time) and aging state (pixel characteristic might change)

Parameter values inside the control software correspond to hardware setting

- Zoom value of the objective lens
- Aperture value of the objective lens
- Focus value of the objective lens
  (measurement plane in focus, focus setting or focus distance provided to the control software)
- Integration time
  - sufficiently long to reach a signal level well above the detection limit but within the dynamic range and to avoid sensor-internal timing issues in the µs-domain
  - integration time should be an integer multiple of the temporal light modulation period
  - avoid blooming as this in general also affects the result from all other pixel) by using an appropriate neutral-density filter (and setting this inside the control software, c.f. neutral density filter).

- Region of interest
  - is each evaluation region many pixels in size and homogeneous?
  - Consider smoothing parameters (i.e. averaging or median filtering)

Verification tests to indicate absence of issues:

- Check zero reading (dark signal measurement, verify the internal offset correction)
- Check measurement of luminance standard
  using different signal levels to verify also non-linearity and absence of significant offset issues (or use a referenced luminance, i.e. by means of an illuminance meter or a luminance spot photometer for a traceability determination of an arbitrary but constant luminance source)
- Check it again >10min later (stability of standard and measurement device)
- Reproducibility (remount objective lens, reset focus, zoom and aperture, rotate filter wheel)

14 Appendix II: List of Measurement Applications

Table of Contents

1 Laboratory - Uniformity of Sources

	Analysis of uniformity of laboratory luminous sources for calibration at different luminance levels

ILMD Type	I
Measurand	cd/m²
FOV / (mm/°)	0.1° to 5° aprox.
Lens type	
Resolution	
L_{min}, L_{max}	10, 10000
Contrast local/ contrast global	local

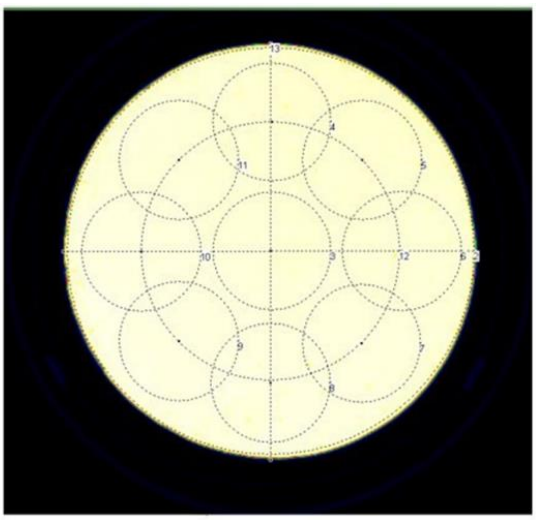
Type of Light Source	Any
Measurement conditions	Typical laboratory conditions
Required Uncertainty / Traceability	Relative measurements
Parameters during the measurement	Constant
	Varying FOV, configuration of exposure time and aperture
Quality indices	

Sample image with evaluation regions:

Examples of evaluation in a reference source used for calibration. In this case: there is a diffuser placed in the outlet port of an integrating sphere. Other types of extended sources could be evaluated following this example.

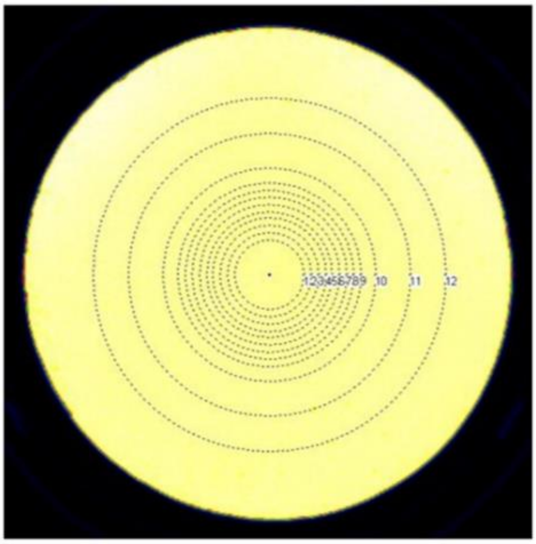
The source was dimmed and evaluated at different *L* values, but only two examples of the tests done are shown.

Measurement



Sample results

Circle N#	$L_{average}$ (cd/m²)		
3	630.9		
4	635	L_{max} (cd/m²)	635.0
5	632.7	L_{min} (cd/m²)	630.9
6	631.5		
7	632.2	Uniformity within:	
8	634.2	0.6499%	
9	634.8	$(L_{max}-L_{min})/L_{min}$	
10	633.7		
11	634.8		



Circle N#	*Diameter (mm)*	$L_{average}$ (cd/m²)		
1	5	29.79		
2	6	29.79	L_{max} *(cd/m²)*	29.91
3	7	29.82	L_{min} *(cd/m²)*	29.79
4	8	29.82		
5	9	29.82	Uniformity within:	
6	10	29.82	0.4028%	
7	11	29.82	$(L_{max}-L_{min})/L_{min}$	
8	12	29.82		
9	13	29.84		
10	15	29.84		
11	20	29.89		
12	25	29.91		

Sample results: analysis of maximum, minimum, average, uniformity and standard deviation of Luminance.

2 Advertising – Luminous Signal

Spanish regulation (ROYAL DECREE 1890/2008, of November 14) for the energy efficiency in outdoor lighting installations	Measurement of luminance and analysis of uniformity on dynamic luminous signals used in advertising

ILMD Type	I
Measurand	cd/m²
FOV / (mm/°)	1° to 10° aprox.
Lens type	
Resolution	
L_{min}, L_{max}	50, 10000
Contrast local/ contrast global	

Type of Light Source	Projection systems using different types of sources, as special halogen lamps, HID, or others. Other advertising panels based on LED technology can be analyzed
Measurement conditions	On-site measurements: outdoor Laboratory measurements: typical lab conditions
Required Uncertainty / Traceability	Absolute measurements
Parameters during the measurement	Constant
	Varying FOV, configuration of exposure time and aperture, temperature (specially for in situ outdoors measurements)
Quality indices	L_{max}, $L_{average}$

Sample image with evaluation regions:

Any advertisement with luminous parts, static or dynamic. In the case of screens with variable pictures, the worst case scenario is a white homogeneous screen.

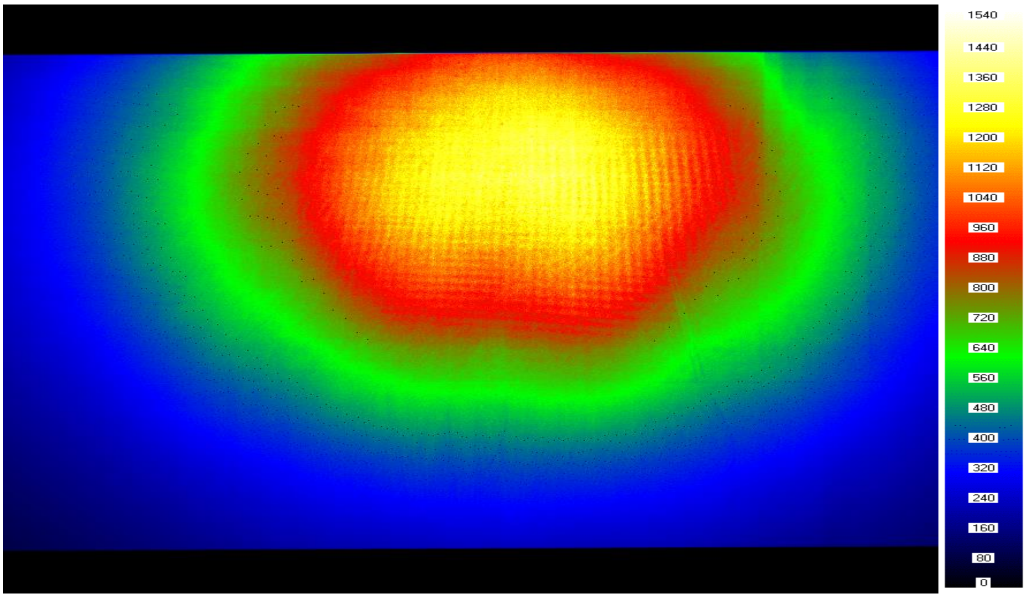
Blank screen projected on storefront (left: from indoors; right: as seen out-doors) where different advertisements or messages are played.

Uniformity of Luminance is an important quality parameter. Nevertheless, the maximum luminance provided by the luminous signal is the regulated parameter. The limit value depends on the dimensions of the screen and the zone where the signal is located (zones 1 to 4, being 1: natural spaces, flora or fauna protection zones, and 4: urban centre, commercial area).

The maximum luminance value is regulated or subject to control of switching on, dimming and switching off in different time periods.

Measurement

~~T~~On axis capture of the area of interest in the different working conditions (regulations of the product). Calculation of the maximum luminance and the average luminance.



Sample results:

Sample results (worst case: 100 % regulation level):

$L_{average}$ = (412.5 ± 2.5) cd/m^2
$L_{maximum}$ = (1538 ± 10) cd/m^2

3 BlackMURA

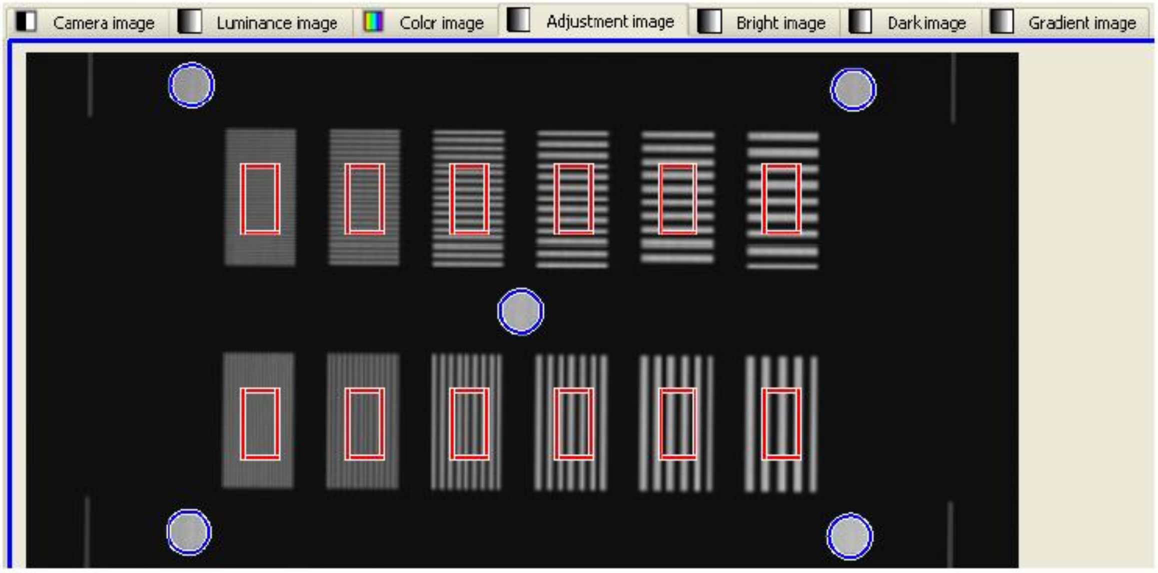
Uniformity Measurement Standard for Displays V 1.2. Pforzeim: DFF e.V. (DEUTSCHES FLACHDISPLAY-FORUM e.V.)	Evaluation of the uniformity of displays especially for the dark state according to (DFF, 2017)

ILMD Type	I
Measurand	BU: L_{min}/L_{max} Gradient in %/mm; or % / pix (Dark Image) Evaluation for Bright and Dark image separately
FOV / (mm/°)	Completely depending on display size (Display captured in one shot)
Lens type	E
Resolution	Camera Pixels / Display Pixels >1
L_{min}, L_{max}	L_{min} > 0.1 cd/m^2 (Dark Image) L_{max} >1000 cd/m^2 (Bright Image))
Contrast local/ contrast global	Local contrast: a few % / mm; Global contrast < 5:1

Type of Light Source	Information Display (usually broad spectra, LCD or OLED), Modulation and Polarization possible; Curved Information Display Warm-up period which bases on luminance stability important as well Sometimes mounting position dependency
Measurement conditions	Precise Geometrical Alignment (perpendicular Alignment of ILMD relative to Display surface and centered) Distance and Lens selection with respect to DUT Field angle influence (try and error test procedure required) → minimal Distance (Lens) Defocus (to Avoid Aliasing) Mean of 10 images
Required Uncertainty / Traceability	All values are relative measurements Practical required uncertainty depends on region of BU For low and high BU; higher uncertainty is sufficient For mid BU (40% till 60%) lower uncertainty is usually required
Parameters during the measurement	Constant: Geometrical Alignment 25 °C ambient temperature Dark Room
	Varying: Distance (boundary), lens type, Focus setting, Reproduction Scale, Integration time
Quality indices	F1’, F21, F31, F32, F8, F12

Sample image with evaluation regions:

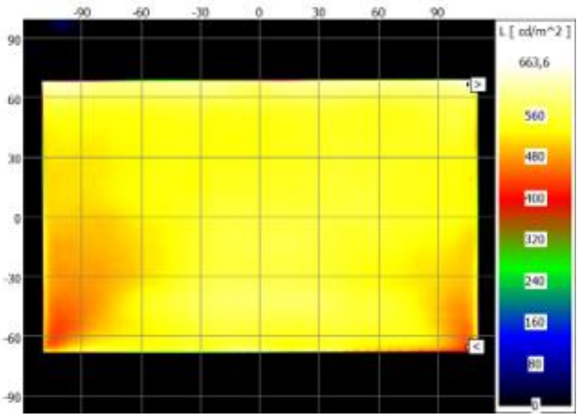
<u>Setup:</u>



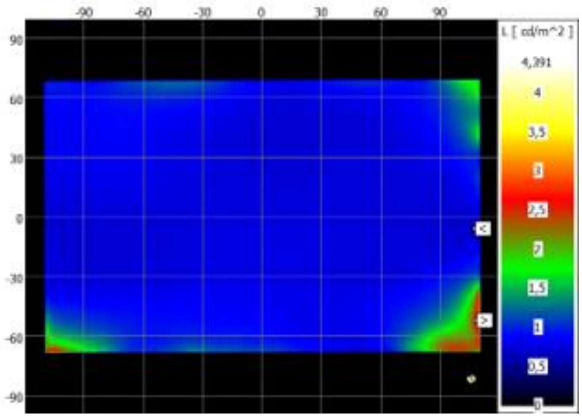
Camera and display related setup (angular adjustment, measurement of reproduction scale, modulation measurement)

Measurement:

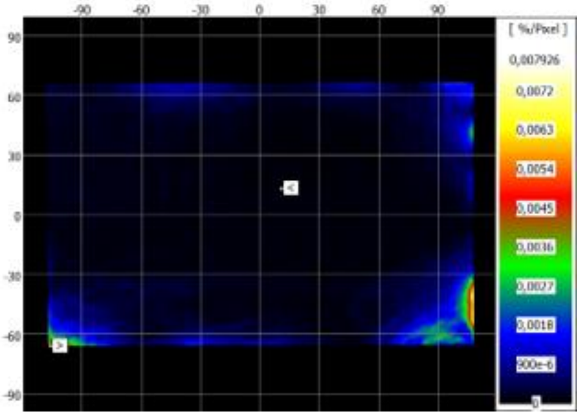
Bright State



Dark state



Gradient calculated from dark state



Sample results:

Parameter	Image	Value	Unit
Mean	Dark image	0.87	cd/m^2
Minimum	Dark image	0.71	cd/m^2
Maximum	Dark image	2.59	cd/m^2
Uniformity	Dark image	27.4	%
Maximum W	Gradient image	0.008	%/px
Maximum B	Gradient image	4.951	%/px
Mean	Bright image	543	cd/m^2
Minimum	Bright image	432	cd/m^2
Maximum	Bright image	637	cd/m^2
Uniformity	Bright image	68	%

References

DFF. (2017). *Uniformity Measurement Standard for Displays V 1.2.* Pforzeim: DFF e.V. (DEUTSCHES FLACHDISPLAY-FORUM e.V.).

4 TI (Threshold Increment)

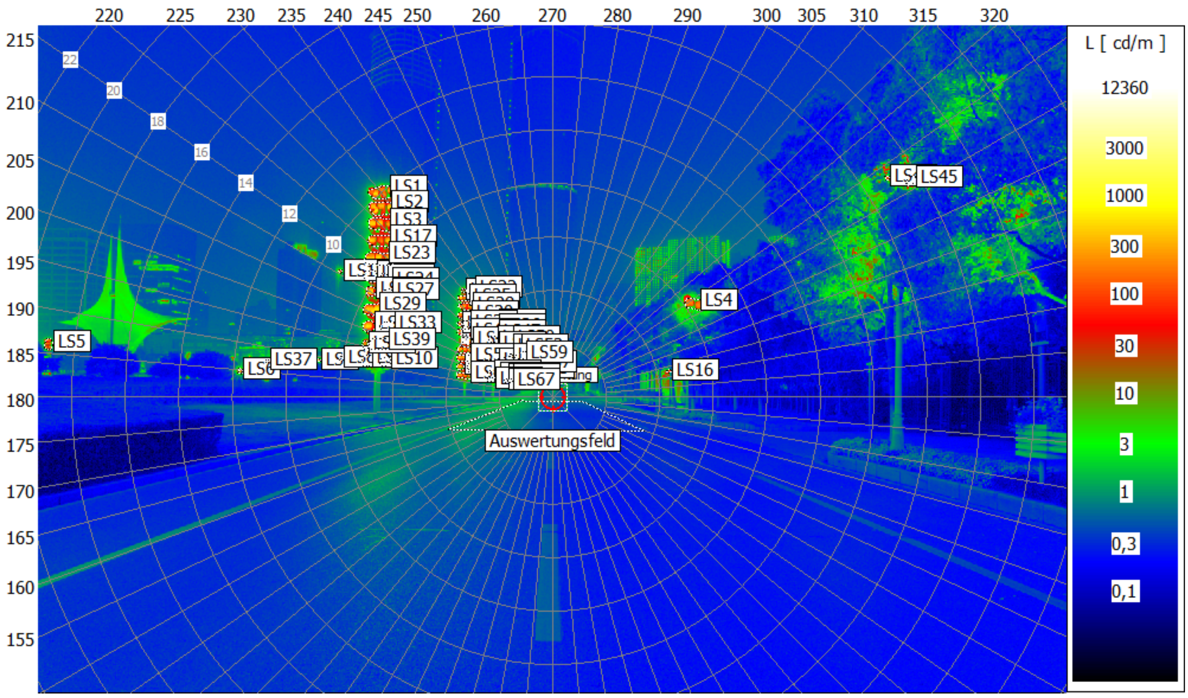
EN13201 – 3: 2016 - Road lighting - Part 3: Calculation of performance	Measuring luminance (cd/m²) of lighting fixtures and road surface under fixed viewing position for specific viewing direction

ILMD Type	I / II
Measurand	%
FOV / (mm/°)	≤ 20°
Lens type	E (wide angle)
Resolution	
L_{min}, L_{max}	0.01, 100
Contrast local/ contrast global	Local

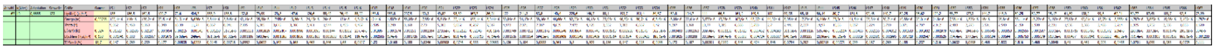
Type of Light Source	Road reflectance and street lighting fixture
Measurement conditions	outdoor
Required Uncertainty / Traceability	
Parameters during the measurement	Constant
	Varying *x*
Quality indices	

Sample image with evaluation regions:

Measurement:



Sample results:



Anzahl	k(Alter)	Adaptation	Schwelle	Größe	Summe	LS1	LS2	LS3	LS4	LS5	LS6	LS7	LS8
67	10	0,6685	123	L(mittel) (cd/m²)		135	186,5	162,5	100,7	72,6	404,7	333,9	135,
				Omega (sr)	0,00236	122,4e-6	146e-6	136,2e-6	79,51e-6	31,31e-6	8,656e-6	3,844e-6	3,84
				Theta (°)		9,962	9,468	9,063	6,348	18,98	11,74	8,867	8,04
				E(vert) (lx)	0,324	0,01628	0,02686	0,02187	0,007954	0,00215	0,00343	0,001268	517,
				L(Schleier) (cd/m²)	0,153	0,001641	0,003	0,002667	0,001975	59,68e-6	249e-6	161,3e-6	80,0
				TI-Wert (%)	13,7	0,147	0,269	0,239	0,177	0,00535	0,0223	0,0145	0,00

5 L20 - Measure: Example 1

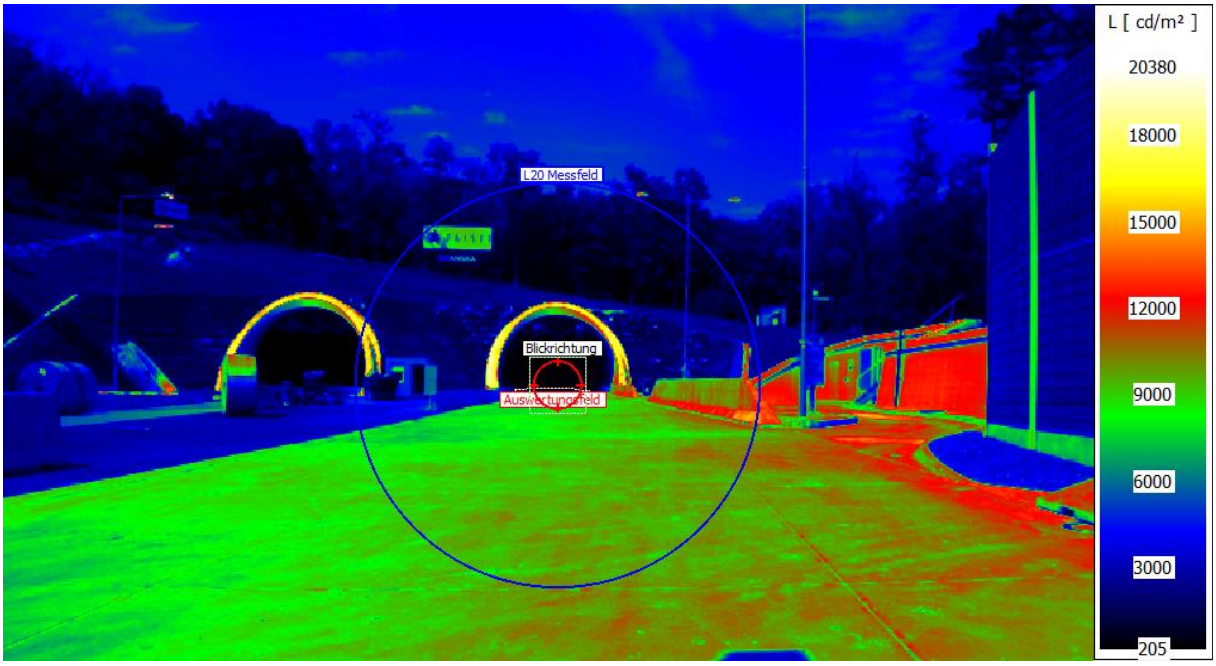
CIE Publ. 88 Guide for the lighting of road tunnels and underpasses	Measuring average luminance (cd/m²) from the surrounding of tunnel entrance lighting fixtures and road surface under fixed viewing position for specific viewing direction

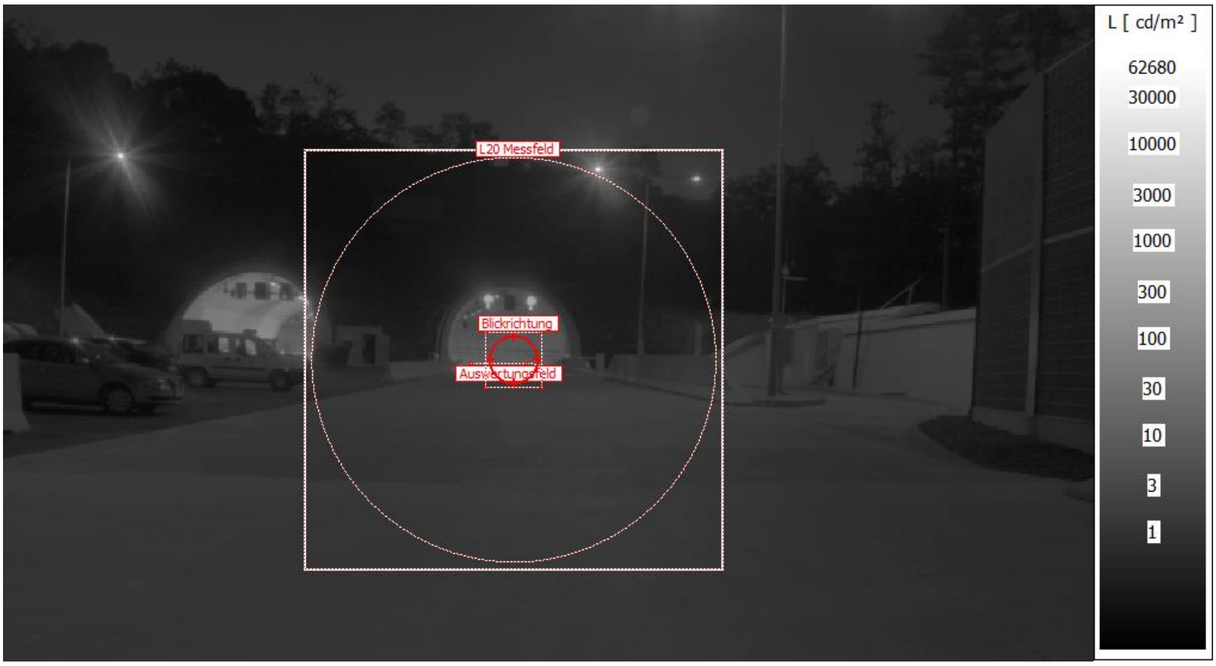
ILMD Type	I / II
Measurand	cd/m²
FOV / (mm/°)	≤ 20°
Lens type	E (wide-angle)
Resolution	
L_{min}, L_{max}	0.01, 100 000
Contrast local/ contrast global	global

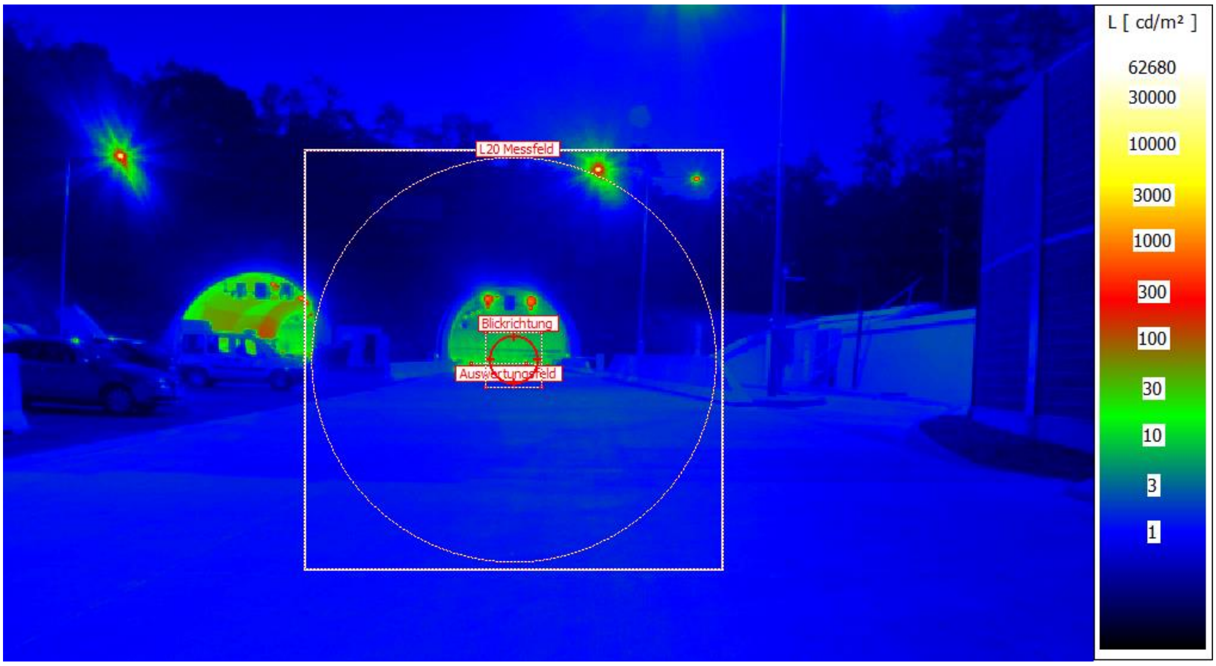
Type of Light Source	Road reflectance and street lighting fixture
Measurement conditions	outdoor
Required Uncertainty / Traceability	
Parameters during the measurement	Constant
	Varying *x*
Quality indices	

Sample image with evaluation regions:

Measurement


L20 Messfeld
Blickrichtung
Auswertungsfeld
L [cd/m²]
20380
18000
15000
12000
9000
6000
3000
205


L20 Messfeld
Blickrichtung
Auswertungsfeld
L [cd/m²]
62680
30000
10000
3000
1000
300
100
30
10
3
1



Sample results:

L20 Messfeld	Geschwindigkeit (km/h)	Schwellwertfaktor k	L(th) = k * L20	L(mittel) Auswertungsfeld
5690	<=60 km/h	0,05	285	657,4
	60-80 km/h	0,06	342	657,4
	80-120 km/h	0,1	569	657,4

6 L20 – Measure: Example 2

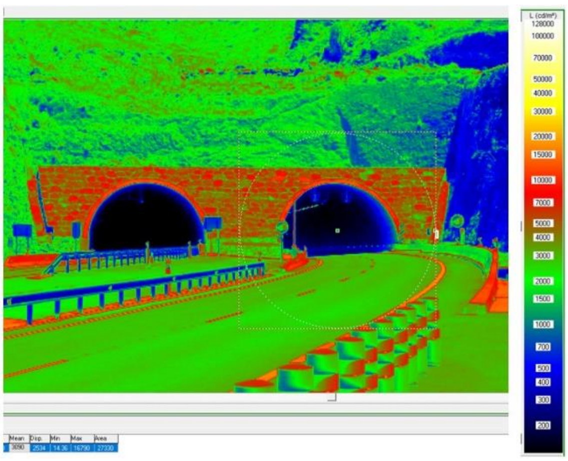
CIE Publ. 88 Guide for the lighting of road tunnels and underpasses	Measuring luminance values of road surface on tunnel entrance under fixed viewing position for specific viewing direction, for FOV ≤ 20°
UNE EN-13201-4: 2016, Road lighting. Part 4: Methods for measuring photometric performance	
Spanish regulation (ROYAL DECREE 1890/2008, of November 14) for the energy efficiency in outdoor lighting installations and its complementary technical instructions EA-01 to EA-07	

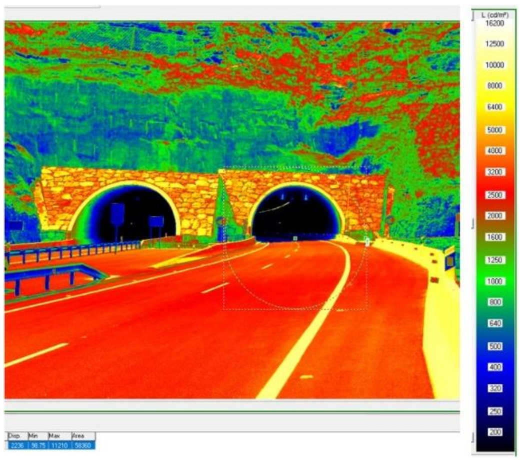
ILMD Type	I
Measurand	cd/m^2
FOV / (mm/°)	≤ 20°
Lens type	
Resolution	
L_{min}, L_{max}	0.01, 100 000
Contrast local/ contrast global	Global

Type of Light Source	Road reflectance and tunnel lighting fixtures
Measurement conditions	Outdoor
Required Uncertainty / Traceability	Absolute measurement
Parameters during the measurement	Constant FOV (20º)
	Varying configuration of exposure time and aperture; temperature (outdoors measurement)
Quality indices	

Sample image with evaluation regions

L_{20} is the average value of luminance within 20° (FOV) at the entrance of a tunnel from the stopping distance, which depends on the maximum allowed speed and other road parameters. The measurement is used to define the lighting needs of the tunnel. This value should be obtained at least in the worst-case (considering the orientation of the tunnel as well as day / time with maximum levels of natural light), it can also be evaluated in different conditions to obtain different configurations for the artificial lighting regulation.





Sample results:

L20 3090 cd/m^2

L20 2843 cd/m^2

7 UGR Measurement

UNE-EN 12464-1:2012 Light and lighting - Lighting of work places - Part 1: Indoor work places	Measurement of background luminance and luminance produced by each luminaire, from each point and direction of interest
Technical Building Code, section HE3 "Energy Efficiency of Lighting Installations"	

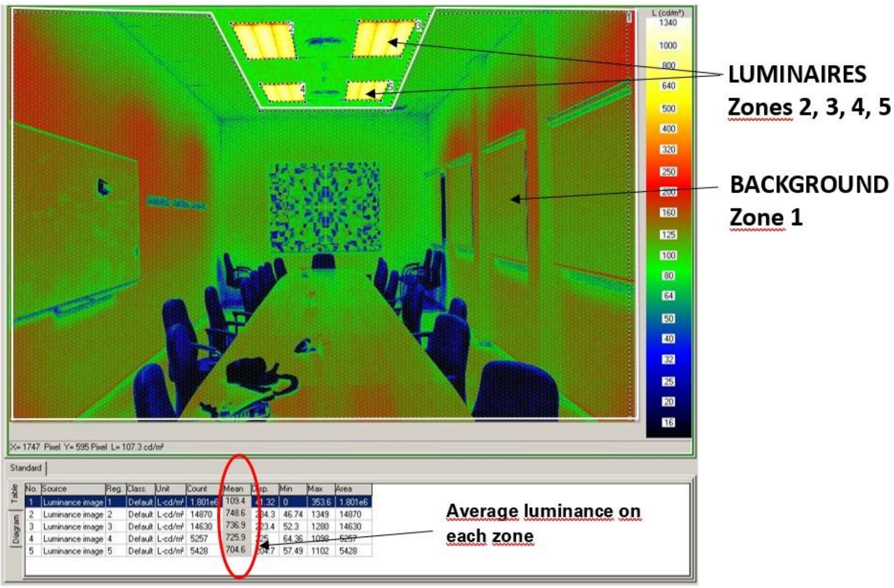
ILMD Type	I
Measurand	UGR value, based on measurement of *L*(cd/m²), position of sources and other geometrical data
FOV / (mm/°)	variable
Lens type	
Resolution	
L_{min}, L_{max}	0.01, 100000
Contrast local/ contrast global	Local / Global

Type of Light Source	Any (currently: typically LED luminaire, white, 3000 K to 5400 K)
Measurement conditions	indoor
Required Uncertainty / Traceability	Absolute measurements
Parameters during the measurement	Constant
	Varying FOV, measurement position and direction, configuration of exposure time and aperture, Temperature (in-situ measurements)
Quality indices	

Sample image with evaluation regions:

On each room (or space) to be evaluated, the points and directions of interest should be defined. Each value of UGR corresponds to one position and sight direction and evaluates the luminance measured from each luminaire as well as the background luminance.

Measurement **Sample results**



Ref. point	UGR
N. 1	16
N. 2	14
N.3	11
N. 4	14
N. 5	11

8 Luminance Measurements in Tunnels

CIE Publ. 88 Guide for the lighting of road tunnels and underpasses	Measuring luminance (cd/m²) of road surface on tunnel entrance and transit zones under fixed viewing position for specific viewing direction
UNE EN-13201-4: 2016, Road lighting. Part 4: Methods for measuring photometric performance	
Spanish regulation (ROYAL DECREE 1890/2008, of November 14) for the energy efficiency in outdoor lighting installations and its complementary technical instructions EA-01 to EA-07	

ILMD Type	I
Measurand	cd/m²
FOV / (mm/°)	6’ (vertical) × 20’ (horizontal)
Lens type	E (wide-angle)
Resolution	
L_{min}, L_{max}	0.01, 10 000
Contrast local/ contrast global	Local / Global

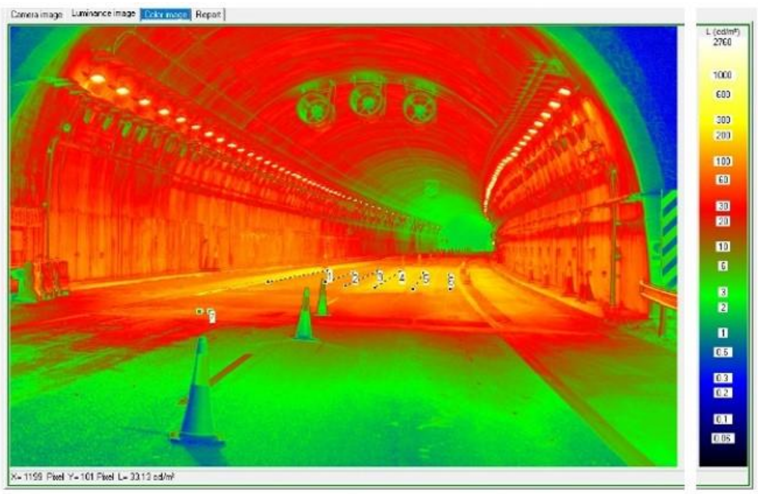
Type of Light Source	Tunnel lighting fixtures and emergency lighting
Measurement conditions	outdoor
Required Uncertainty / Traceability	Absolute measurements
Parameters during the measurement	Constant: Measurement position and FOV (in each zone to be evaluated)
	Varying: Direction of measurement for the different points. Configuration of exposure time and aperture. Temperature (out doors measurements)
Quality indices	

Sample images in different parts along the tunnel, with different lighting configurations (entrance, transit, emergency):

Measurement and results

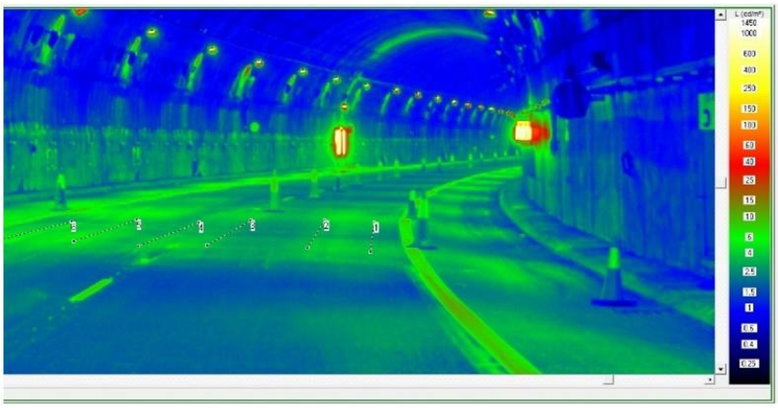
Measurements of luminance along three lines on each lane. Average values and uniformity are calculated.

Entrance of the tunnel:



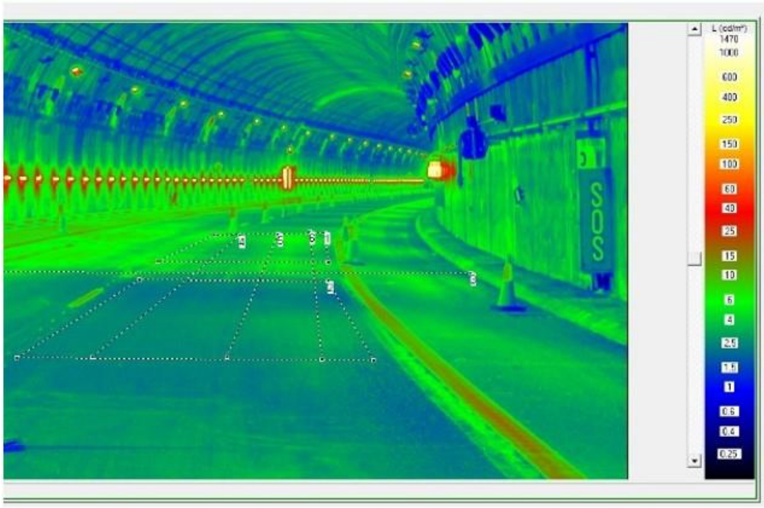
Zone#	$L_{average}$ (cd/m²)
4	*196.0*
5	*181.6*
6	*173.6*

Inside part of the tunnel:



Zone#	$L_{average}$ *(cd/m²)*
1	*3.460*
2	*3.708*
3	*3.456*

Inside part of the tunnel with emergency lighting:



Zone#	$L_{average}$ *(cd/m²)*
4	*2.990*
5	*3.409*
6	*3.522*

9 Street Lighting EN13201 Measuring grid

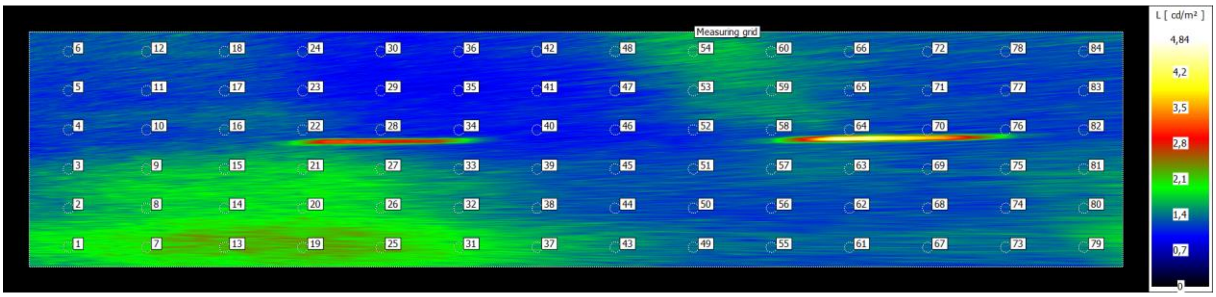
EN 13201-3:2015 Road lighting - Part 3: Calculation of performance	Measuring luminance (cd/m²) of road surface under fixed viewing conditions for specific point grid raster

ILMD Type	I / II
Measurand	cd/m²
FOV / (mm/°)	≤ 20°
Lens type	E (telecentric)
Resolution	
L_{min}, L_{max}	0.01, 100
Contrast local/ contrast global	Global

Type of Light Source	Road reflectance of street lighting fixture
Measurement conditions	outdoor
Required Uncertainty / Traceability	
Parameters during the measurement	Constant
	Varying: *x*
Quality indices	

Sample image with evaluation regions:

Sample results:



Number of grid lines	1	2	3	4	5	6	7	8	9	10	11	12	13	14	L_Max	L_Min	L_Avg	Lengthwise Uniformity	Overall Uniformity
6	1.32	1.37	1.34	1.16	1.07	1.08	1.17	1.37	1.63	1.52	1.36	1.31	1.29	1.28	1.63	1.07	1.4	0.658	0.696
5	1.24	1.24	1.25	1.11	1	0.971	1.03	1.12	1.43	1.47	1.32	1.26	1.2	1.22	1.47	0.971		0.659	
4	1.28	1.22	1.33	1.29	1.13	1.04	1.06	1.09	1.2	1.32	1.3	1.21	1.24	1.21	1.33	1.04		0.778	
3	1.48	1.67	1.7	1.78	1.68	1.4	1.32	1.28	1.29	1.37	1.42	1.33	1.38	1.44	1.78	1.28		0.721	
2	1.52	1.75	1.81	1.84	1.77	1.54	1.39	1.26	1.24	1.22	1.24	1.25	1.27	1.45	1.84	1.22		0.664	
1	1.89	2.06	2.21	2.22	2.21	1.96	1.66	1.52	1.41	1.37	1.38	1.38	1.39	1.5	2.22	1.37		0.618	

10 Photobiological safety

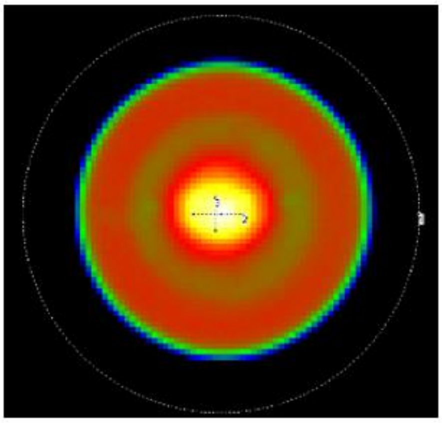
Dimensional measurement of the luminous area with emission above 50% of maximum, identification of the FOV to be evaluated in different configurations	UNE-EN 62471:2009: Photobiological safety of lamps and lamps systems
UNE-EN 62471:2009: Photobiological safety of lamps and lamps systems	

ILMD Type	I
Measurand	cd/m²
FOV / (mm/°)	1.7 mrad to 100 mrad
Lens type	
Resolution	
L_{min}, L_{max}	50, 100 000; neutral filter needed in some cases
Contrast local/ contrast global	Local

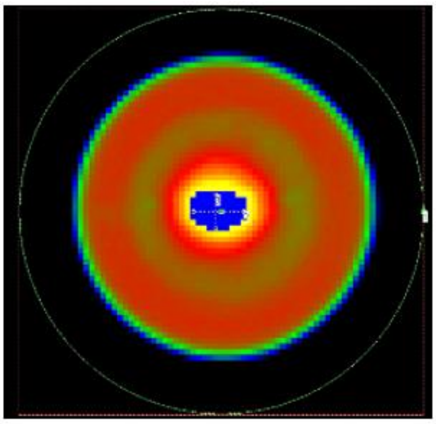
Type of Light Source	Any (typically LED sources: white or color)
Measurement conditions	Typical laboratory conditions
Required Uncertainty / Traceability	Relative measurements
Parameters during the measurement	Constant
	Varying: FOV, configuration of exposure time and aperture accordingly to the characteristics of the product
Quality indices	Area with Luminance above 50% of maximum luminance

Examples of evaluation in different products

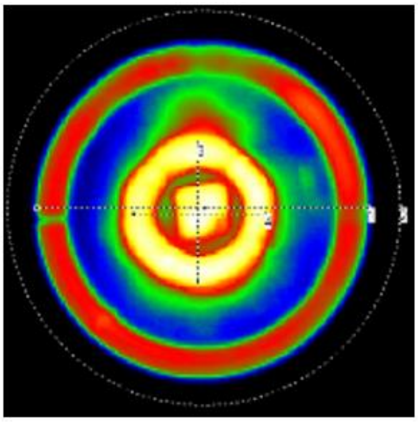
The emitting surface of the source is analysed, the actual dimensions of the area with luminance ≥ 50% of the maximum luminance allows the classification of the source as “small” or “non-small”, which conditions how the blue light hazard should be evaluated, obtaining radiance or irradiance values, having different limiting values per risk category.



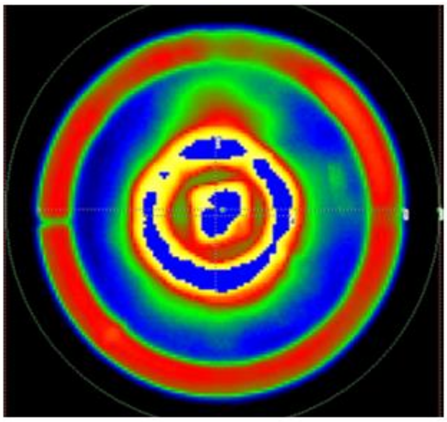
Luminance image



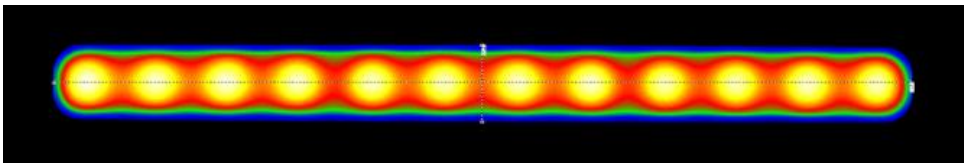
Processed image: $L \geq 50\% \, L_{max}$ in solid blue central area



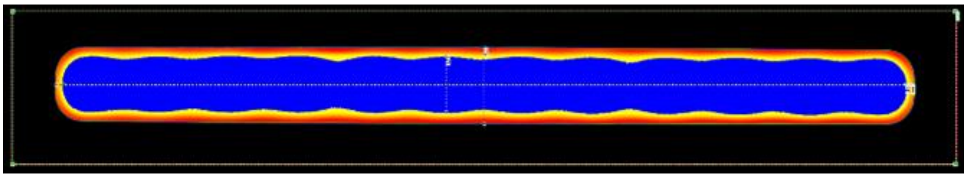
Luminance image



Processed image: L ≥ 50% L_{max} in solid blue areas



Luminance image



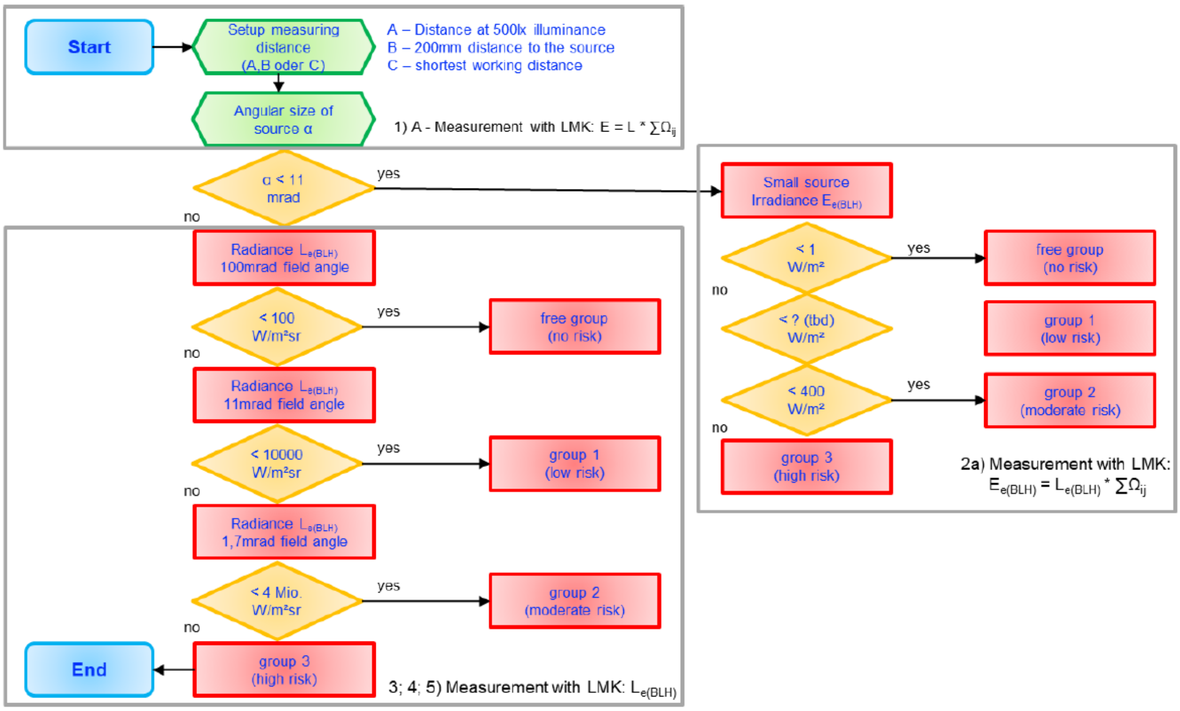
Processed image: L ≥ 50% L_{max} in solid blue area

11 BLH – Blue light hazard

EN 62471 – photobiological safety of lamps and lighting systems	Measuring radiance W/ (m² · sr) and irradiance (W/m²) of lighting fixtures under fixed direct viewing conditions into the light source

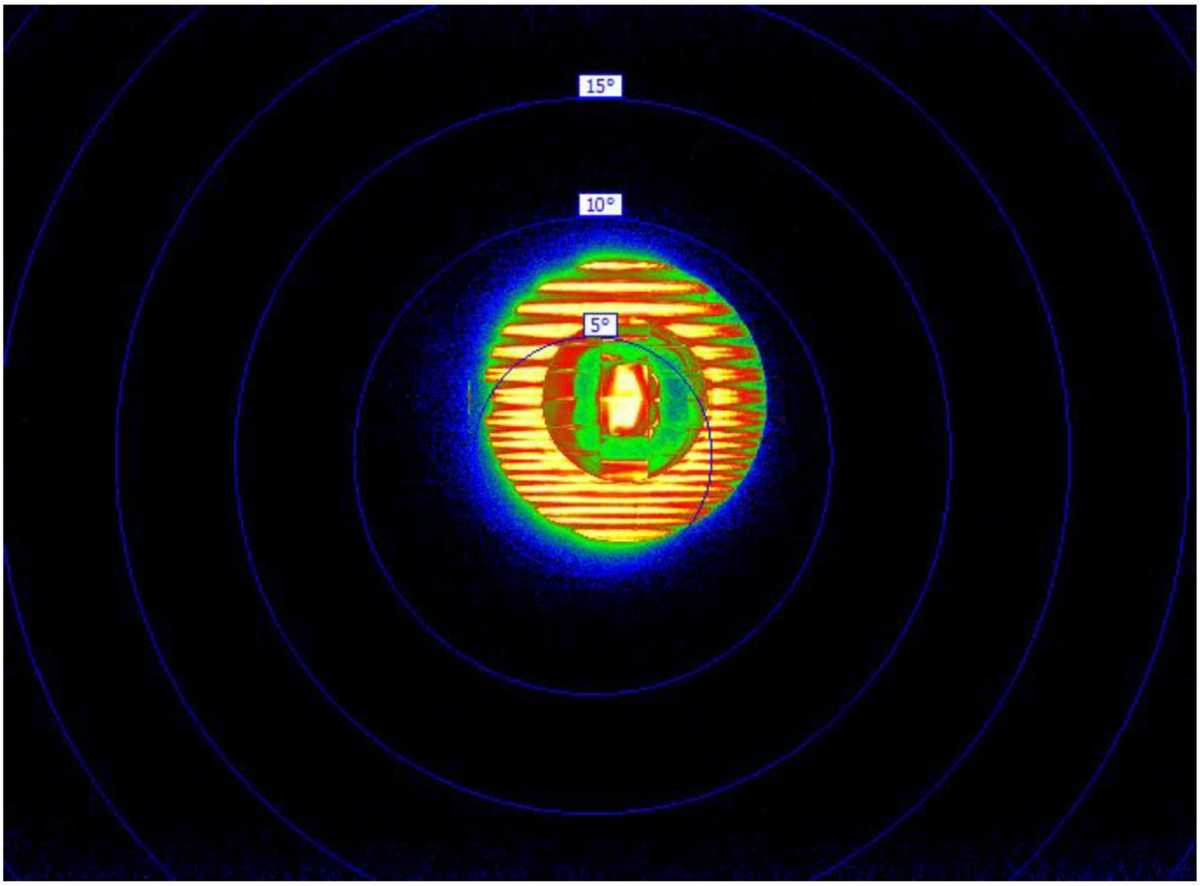
ILMD Type	I / II
Measurand	W/ (m² · sr)
FOV / (mm/°)	
Lens type	E
Resolution	certain measurement angles or aperture angles must be used: 100 mrad (5.73°); 11 mrad (0.63°) or 1.7 mrad (approx. 0.1°)
L_{min}, L_{max}	
Contrast local/ contrast global	Local

Type of Light Source	Not specified	
Measurement conditions	Test set up	
Required Uncertainty / Traceability		
Parameters during the measurement	Constant *x*	
	Varying	
Quality indices		

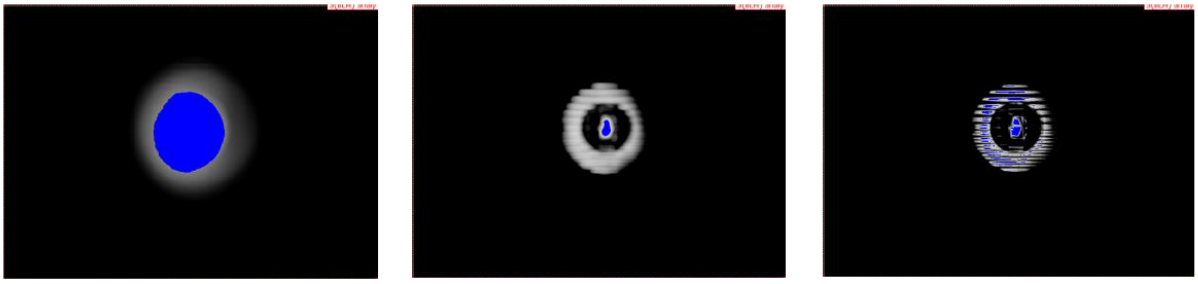


Overview of the standardized sorting into risk groups of EN 62421

Sample image with evaluation regions:



BLH filtered/weighted image with 100 mrad (left), 11 mrad (middle) and 1.7 mrad (right) aperture combined with the display (blue coloured) of the 50 % emission threshold to determine the size of the active angular area α in mrad:



Sample results:

Stat.No.	Parameter	Image	Region	Class	Area	Min	Max	Mean	Disp	BLH Irradiance (W/m²)	BLH angular size (mrad)
					pix^2	W/sr*m²	W/sr*m²	W/sr*m²	W/sr*m²		
1	Lum_Gr[91]	BLH image 100 mrad	S(BLH) analysis	> 212.75 W/sr*m²	519900	212,8	425,5	296,9	61,31	7,053	174
2	Lum_Gr[92]	BLH image 11 mrad	S(BLH) analysis	> 1203.0 W/sr*m²	11880	1203	2406	1678	318,6	0,911	26,29
3	Lum_Gr[93]	BLH image 1.7 mrad	S(BLH) analysis	> 1528.5 W/sr*m²	46090	1529	3057	1847	300,7	3,888	51,78