21NRM01 HiDyn

{HiDyn}

D2: Good practice guide describing the characterisation of different HDR imaging instruments, such as ILMDs and RGB matrix sensor cameras, based on the recommendations stated in CIE 232:2019 and CIE 244:2021.

Organisation name of the lead participant for the deliverable: CMI

Due date of the deliverable: 31 March 2025

Actual submission date of the deliverable: 28 November 2025

Glossary

ADC   Analog to Digital Converter

BRDF   Bidirectional Reflectance Distribution Function

CIE   International Commission on Illumination

DN   Digital number

GT   Ground truth

GPG   Good Practice Guide

GUM   Guide to the expression of uncertainty in measurement

DUT   Device Under Test

HDR   High Dynamic Range

ILMD   Imaging Luminance Measurement Device

PRNU Photo-Response Non-Uniformity

PSF   Point Spread Function

SMFC Spectral Mismatch Correction Factor

SNR   Signal-to-Noise Ratio

SPD   Spectral power distribution

TABLE OF CONTENTS

{HiDyn}

1 Summary

This Good Practice Guide describes the experimental procedures proposed for characterizing the effect of the different sources of errors in the measurement of the luminance with HDR imaging instruments, such as ILMDs, multispectral cameras or RGB matrix sensor cameras. Specifically, this document explains in detail the experimental procedures to be followed using the reference high-contrast light source designed and developed during the 21NRM01 HiDyn project.

2 General overview

The characterization is based on the idea that a number of well-defined light sources (in size, shape and luminance) with different levels of luminance **can be used to define several well-defined high-contrast scenes to be used as ground-truth (GT)**. These GTs are used as references to evaluate how well an HDR imaging measurement system can measure simultaneously different luminance levels, and to characterize the relevant parameters for the luminance measurement model.

For the characterization, the users have to apply the following workflow, illustrated below (Figure 1):

1. Geometrically realize a set of luminance configurations (see Section 6). These configurations include cases where only one light source module is switched on, where all source modules are switched on simultaneously, and dark conditions. Configurations for two types of procedures are defined: (1) **Fundamental**, where the field of view includes all source modules (Section 6.1); and **External Stray Light**, where the field of view excludes the external source modules (Section 6.2).

2. Obtain, for each configuration, images acquired with the imaging measurement system under evaluation, in which the pixel values are directly related to luminance. These images must be HDR images, with a high signal-to-noise ratio (SNR) across all pixels.

3. Calculate from these images the different parameters or quality indices, as explained in Section 7.
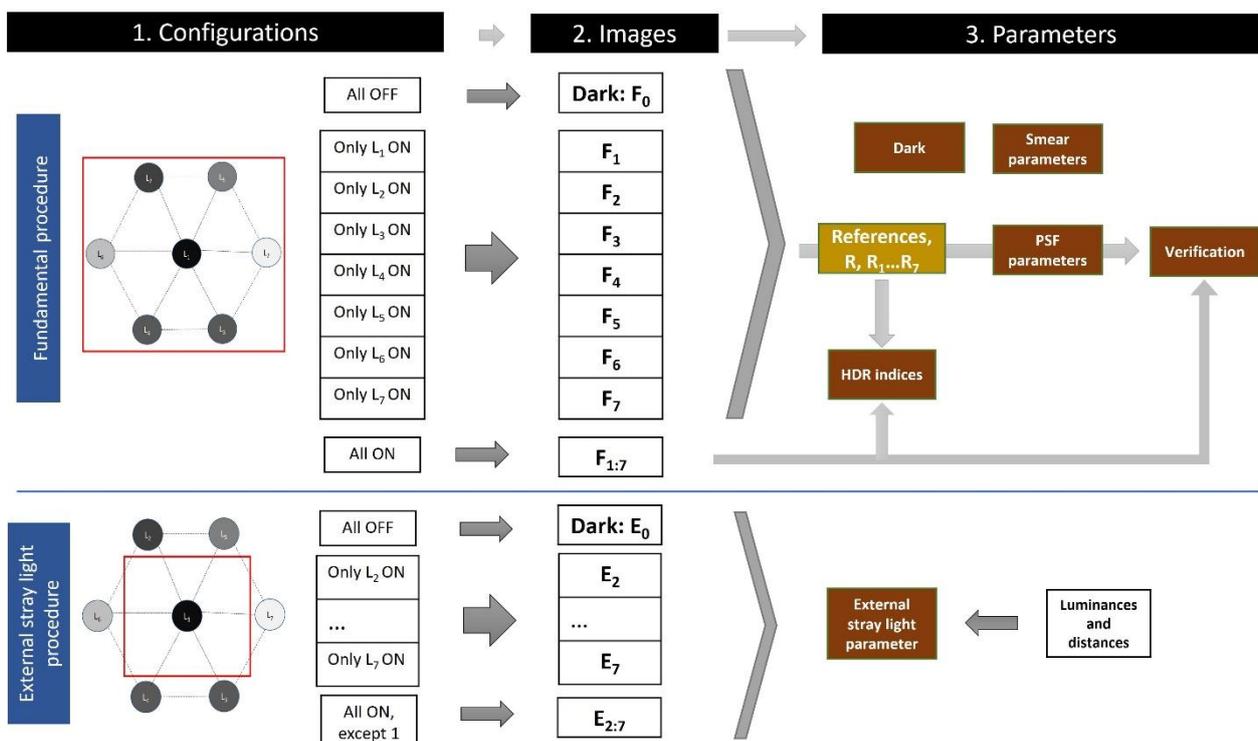

Figure 1: Overview of the characterization workflow

3 Introduction

The response of a detection element (pixel) of a luminance imaging measurement system is related to the luminance of the object at the corresponding position in the object plane, but also to the integration time, which is the time of accumulation of the photoelectrons produced by the absorbed photons. The adequate number of photoelectrons for an acquisition excludes levels lower than a minimum number, for which the signal-to-noise ratio (SNR) is too low, and levels higher than a maximum number above which saturation (nonlinearity effects) or ADC (Analogue to Digital Converter) clipping happens. When there is a large range of radiance or luminance present in a scene, the most typical strategy for obtaining adequate numbers of electrons in all pixels is by using different integration times for different luminance levels. This strategy of obtaining signals from an image sequence allows the dynamic range of the measurement to be greatly enlarged in comparison with that from a single acquisition at a fixed integration time. The resulting image is known as a high-dynamic-range (HDR) image, and the measuring process is referred to as HDR imaging.

This kind of HDR image potentially contains the information needed to measure simultaneously a wide range of luminance (several orders of magnitude), because the response of all pixels is produced by an adequate number of photoelectrons. However, an adequate SNR does not always guarantee an accurate luminance measurement, especially for low luminance values, where the most impacting source of error may be related to stray light: the response to the stray light produced by the brightest light sources in the scene is comparable to the response to the dimmest light sources and cannot be subtracted in a simple way. In other words, the brightest source occludes the dimmest ones. This stray light, as radiant flux collected by the matrix detector in positions different to the corresponding positions on the object plane, can be caused by inter-reflections, diffusion or diffraction by the objective lens. Some effects of this stray light can be corrected by deconvolution or other methods, as for instance when the point spread function (PSF) is known, but other effects are non-correctable artefacts which can only be evaluated as sources of uncertainty. The consequence is a decrease in the range of luminance that can be measured simultaneously.

The errors introduced by this issue notably affect applications for which the measurable luminance range is important, such as in glare evaluation. In this case, the several indices defined require the luminance of both the bright light sources and the dim background as input variables, to which the index is similarly sensitive.

To fully explore the potential and limitations of HDR imaging measurement systems, well-defined references are required to quantify the dynamic range of a given measurement system under specific high-contrast conditions. This Good Practice Guide (GPG) describes a method for the photometric characterization of HDR imaging systems using a high contrast luminance reference light source, in order to estimate measurement uncertainty. The spatial configuration of the reference light source is defined, together with the methods proposed to obtain the relevant empirical parameters needed for evaluating the capability of these systems to reliably measure high-contrast luminance scenes.

The CIE technical report CIE 244:2021 "Characterization of Imaging Luminance Measurement Devices (ILMDs)" [CIE 2021] recommends new quality indices for imaging luminance measurement devices (ILMDs), which are not defined for conventional luminance meters with no spatial resolution. These indices quantify, from 0 to 1, the general impact of different error sources on the measurements for a given instrument. These indices are: (1) Responsivity uniformity for flatfield, f_{21}; (2) Responsivity uniformity for spots, f_{22}; (3) Effect of surrounding field, f_{23}; (4) Stray light influence for negative contrast, f_{24}; (5) Edge function, f_{25}; (6) Influence of smear, f_{26}; (7) Shutter repeatability, f_{27}; (8) Aperture repeatability, f_{28}; (9) Size-of-source effect, f_{29}.

The properties that these quality indices aim to quantify are usually determined by error sources that can be characterized using the high-contrast reference source developed during the HiDyn project [HiDyn 2025], except for the error source related with f_{21} and f_{22} (Photo-Response Non-Uniformity). Additionally, the proposed characterizations address the determination of measurement uncertainties, unlike the above-mentioned quality indices, which serve as reference indices for comparing instruments and cannot be used to estimate uncertainties. In appendix 1 of CIE 244:2021 [CIE 2021], a measurement model is recommended for evaluating uncertainty. In this GPG, this report proposes a modification to account for the effects of internal and external stray light and smear.

The characterization of the Photo-Response Non-Uniformity (PRNU) of the imaging measurement systems does not require the availability of the high-contrast luminance reference source, rather, it relies on high-

uniformity luminance references such as integrating spheres. This is also briefly discussed in this GPG. The CIE technical report CIE 232:2019, "Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance" [CIE 2019], proposes a glare metric for large and non-uniform luminaires. To use this metric, the flatfield correction of the imaging measurement system must be characterized, especially when the luminaire is very large and the PRNU of the instrument strongly impacts the measurement of the non-uniformity of the luminaire as well as of the luminance values.

4 Measurement model

A model is given here for the measurement with HDR imaging measurement systems, where the different sources of error are explicitly expressed:

$$L_{V,k} = \frac{F_T}{s_V F_{NU,k} F_{SM,k}} \left(\frac{w_{n,k}}{t_{e,k}} - \sum_{i \neq k} (\eta_{k,i} + \chi_{k,i}) \frac{w_{n,i}}{t_{e,i}} - \zeta E_{bg} \right) \quad (1)$$

with:

$$w_{n,j} = (w_j - w_{0,\text{off},j})/F_{NL,j} - F_j \cdot r_{th,j} \cdot t_{e,j} \quad (2)$$

The variables and functions involved in these equations are given in Table 1.

This model considers as input the direct response of a linear camera (w), ideally proportional to the radiant exposure. For instruments that directly provide measurement values already adjusted as luminance (L_V'), that quantity should replace $\frac{w_{n,k}}{t_{e,k}}$ in Eqs. (1)-(2).

Table 1. Variables and functions involved in the measurement model.

Name of the variable	Symbol of the variable / X_i	SI units[*)]
Luminous responsivity in luminance	s_V	DN·s^{-1}·cd^{-1}·m²
Temperature factor	F_T	-
Out-of-field illuminance	E_{bg}	lx
Rate of out-of-FOV stray light	ζ	DN·s^{-1}·lx^{-1}
Normalized signal of pixel j	$w_{n,j}$	DN
Exposure time for pixel k	$t_{e,k}$	s
Normalized signal of pixel i	$w_{n,i}$	DN
Exposure time for pixel i	$t_{e,i}$	s

Name of the variable	Symbol of the variable / X_i	SI units[*]
Normalized signal of pixel $f_G(k)$	$w_{n,f_G(k)}$	DN
Optimal exposure time for pixel $f_G(k)$	$t_{e,f_G(k)}$	s
Smear function from pixel i to pixel k	$\chi_{k,i}$	-
[**] Stray light function from pixel i to pixel k	$\eta_{k,i}$	-
Luminance at pixel k	$L_{V,k}$	cd·m^{-2}
Value of signal of pixel j	w_j	DN
Value of dark offset of pixel j at $t_e \rightarrow 0\ s$	$w_{0,\text{off},j}$	DN
Non-uniformity factor	$F_{\text{NU},j}$	-
Spectral mismatch correction factor	$F_{\text{SM},j}$	-
Non-Linearity correction factor	$F_{\text{NL},j}$	-
Exposure time	$t_{e,j}$	S
Rate of thermally generated electrons	$r_{\text{th},j}$	n·K^{-1}·s^{-1}
Conversion factor	F_j	DN·K·n^{-1}
Normalized response	$\mathbf{w_{n,j}}$	**DN**

[*] DN is number of digital counts and n is number of electrons.

[**] Only the diffuse component of the stray light, which can be described by the PSF, is addressed in this document. The description of the regular component of the stray light due to complex regular inter-reflections, commonly known as ghosts, requires the characterization of different functions to model the different effects, and its correction is complex. The potential impact of these ghosts must be considered in the uncertainty budget.

These variables and functions need to be obtained to provide the measurement of luminance with HDR imaging measurement systems. The high contrast reference source developed in this project would allow some of them to be characterized whereas the determination of other parameters require further procedures.

5 Spatial configuration of the high contrast reference source

The **spatial configuration** refers to the relative position of the individual light source modules composing the high contrast reference source. It is only a part of the **luminance configuration**, where it is also defined which of those individual light source modules are turned on.
The relevant information for defining the spatial configuration is:

1) The relative position of the light source modules, with a 2-D vector, whose components might be expressed in length units, pixels or even in degrees, depending on the case.
2) The luminance level of each light source module.

In the proposed procedure, the spatial configuration is a regular hexagon with side pitch *d.* The dimmest light source module is positioned at the centre of the hexagon, with a light trap nearby, whereas the other individual light source modules are placed at the vertices. The individual light source modules are arranged so that the light source module at the opposite vertex is only one decade of luminance larger or lower.

The spatial configuration is detailed in Table 2 and shown in Figure 2:

Table 2: Spatial configuration of the high contrast source for characterizing HDR imaging measurement systems.

Source symbol	Luminance level	X – position	Y – position
L_0	L_0: Luminance of the light trap	$C_x + \varepsilon$	$C_y + \varepsilon$
L_1	L_1: Luminance of the dimmest light source module	C_x	C_y
L_2	L_2: $\cong 10 \times L_1$	$C_x - d/2$	$C_y + d^{1/2}/3$
L_3	L_3: $\cong 10^2 \times L_1$	$C_x + d/2$	$C_y - d^{1/2}/3$
L_4	L_4: $\cong 10^3 \times L_1$	$C_x - d/2$	$C_y - d^{1/2}/3$
L_5	L_5: $\cong 10^4 \times L_1$	$C_x + d/2$	$C_y + d^{1/2}/3$
L_6	L_6: $\cong 10^5 \times L_1$	$C_x - d$	C_y
L_7	L_7: $\cong 10^6 \times L_1$	$C_x + d$	C_y

$(C_x - d/2, C_y + d^{1/2}/3)$ $(C_x + d/2, C_y + d^{1/2}/3)$

L_2 L_5

d

d

L_0

L_6 L_1 L_7

$(C_x - d, C_y)$ (C_x, C_y) $(C_x + d, C_y)$

L_4 L_3

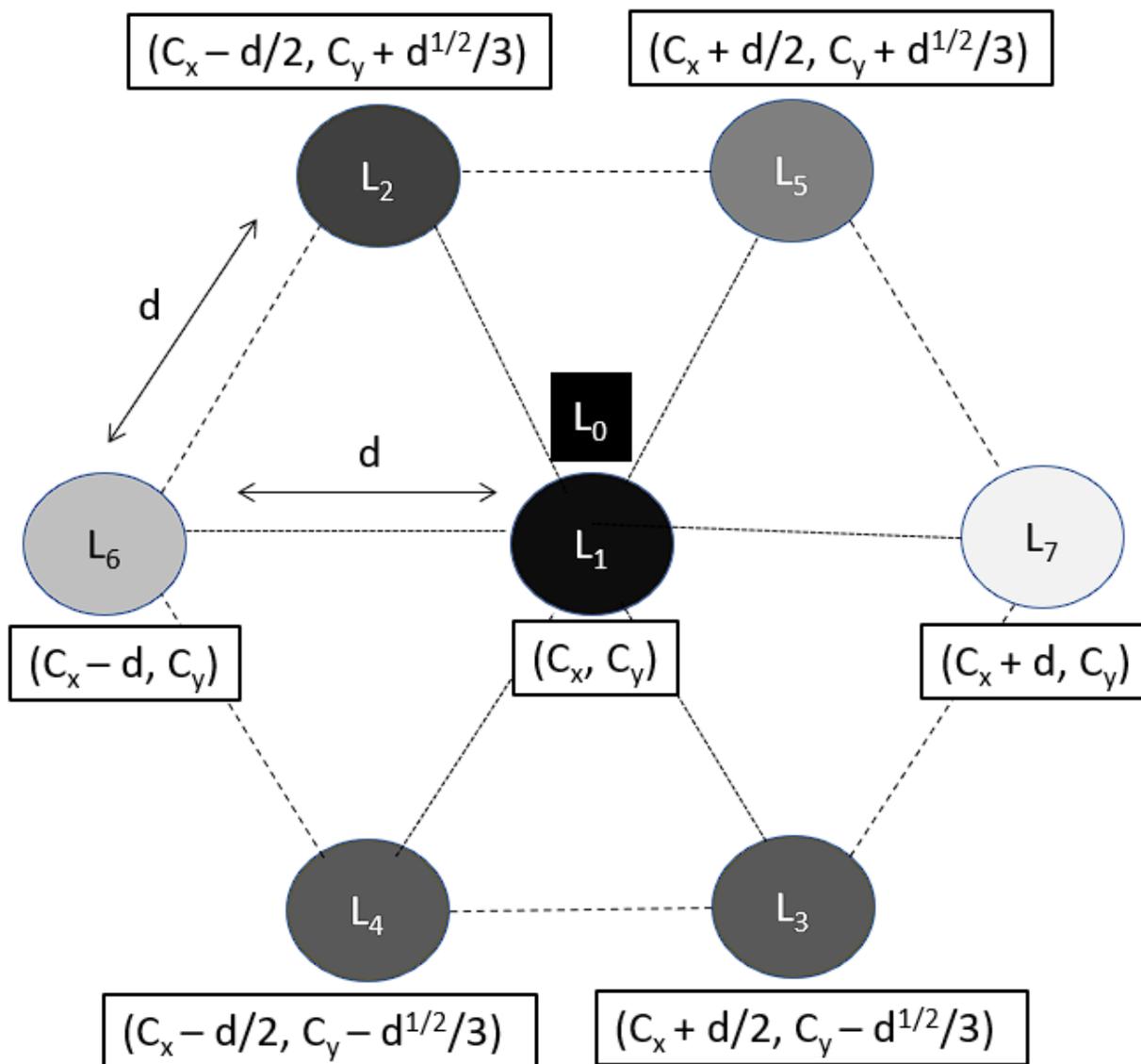$(C_x - d/2, C_y - d^{1/2}/3)$ $(C_x + d/2, C_y - d^{1/2}/3)$

Figure 2: Sketch of the spatial configuration of the components of the high contrast source for characterizing HDR imaging measurement systems.

The arrangement shown in Figure 2 minimizes the impact of specular reflections at the lens of the test camera from very bright to very dim source modules (**cross-talk**). However, these specular reflections should be minimized further by not orienting the optical axis completely perpendicular to the regular hexagon (see Figure 3), as verified in tests by the HiDyn consortium. Other alternatives are possible, including slightly shifting the source modules laterally so they are not symmetric with respect to the camera axis. It is important that the chosen configuration keeps all source modules in focus. It must be noticed that these strategies to reduce cross-talk are more effective when the objective lens has a relatively flat first lens or in case a planar neutral density filter is placed in front of the lens.
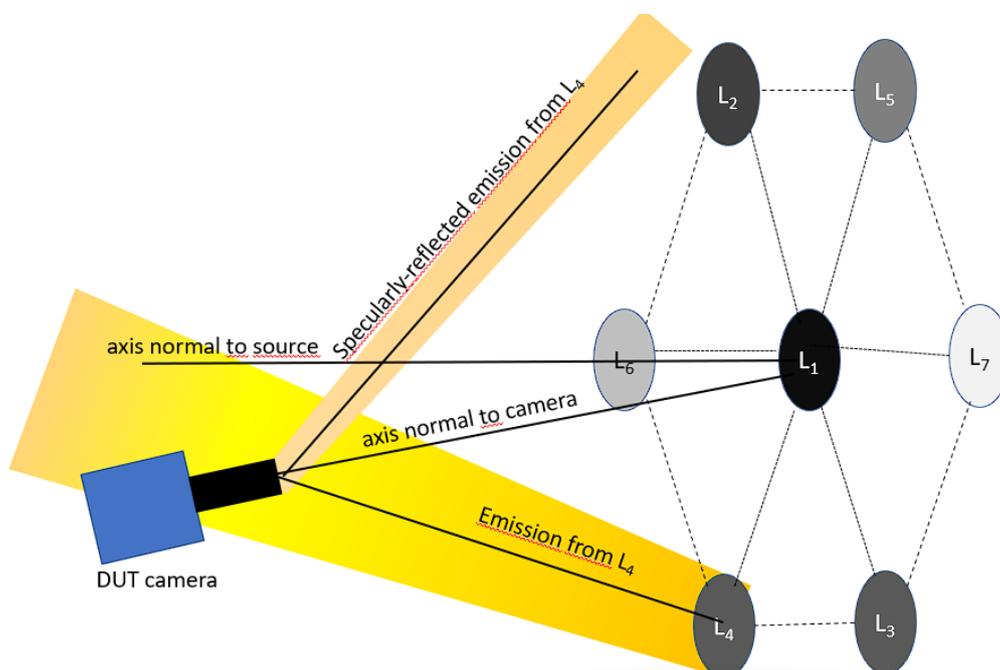
Figure 3: Sketch of the arrangement to minimize cross-talk. It is shown how the slight tilt of the device under test (DUT) camera prevents the specular reflection from L_4 meeting directly L_5. The same occurs with the other pairs of diametrically opposed individual light source modules.

It was observed using a conventional spot luminance meter that, because of cross-talk, an increase of 7% might be obtained in the luminance measurement for the dimmest source module (L_1) when all the source modules are ON at the same time. This error is much smaller than the typical error caused by stray light in this configuration, which is around 100 %. This indicative cross-talk value applies specifically for the camera, objective lens and laboratory used for the tests, as cross-talk is not exclusively related to the source but also depends on these conditions.

6   Experimental procedures

Luminance measurements of the source are carried out with the device under test (DUT, i.e. the HDR imaging measurement system to be characterized). The luminance images will be used to obtain the values of the relevant parameters required for calculating the best estimation and uncertainty of the luminance.

This section describes two different but complementary procedures. Each procedure is defined by (1) **a fixed geometrical configuration of the reference light source with respect to the DUT**, and (2) **a specific sequence of measurements at different luminance configurations**.

In both procedures, the individual light source modules composing the reference light source are aligned with the optical axis towards the centre of the objective lens of the DUT, in a way that the objective lens is uniformly irradiated by the individual source modules.

It is strongly advised to perform the experimental measurements in a room with dark walls and to remove surrounding objects to minimize any light not originating from the reference source (external stray light). In case this is not possible, an option is to operate the camera through a hole in a black curtain to shadow absorb (shadow) the stray light from the room.

6.1   Fundamental procedure

The reference luminance source is **completely** included in the field of view of the DUT and is **well-distributed** within it. To achieve this, the individual light source modules along the horizontal axis of the rectangular field-of-view (with horizontal and vertical dimensions D_x and D_y, respectively), should be positioned at approximately ¼ D_x and ¾ D_x. An example is shown in Figure 4.
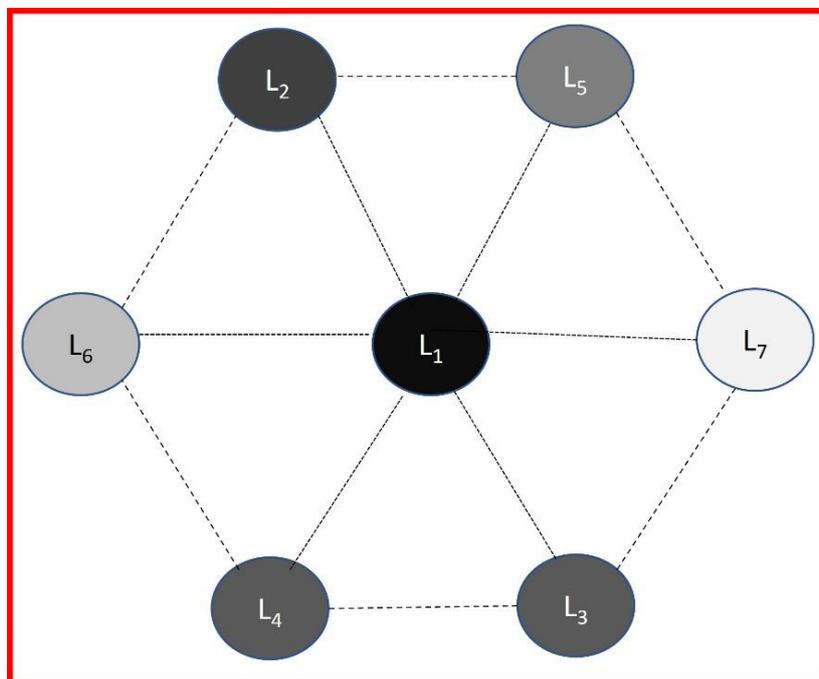

Figure 4: Spatial configuration of the high contrast source with respect to the field-of-view of the DUT (red rectangle), for the **fundamental procedure**. Note that the light source modules must be oriented to the objective lens of the DUT camera and is illuminating (overfill) it completely.

The luminance measurements are carried out for different **luminance configurations**, the difference among them being only the individual light source modules which are turned on (realized by covering with caps to maintain stable operation conditions of the source modules). These configurations are defined in

Table 3. It must be noticed that, in all configurations, the caps of individual light source modules must be removed.

Table 3: Luminance configurations for the **fundamental procedure**. The need for each configuration is described in the third column.

Configuration id.	Light source modules turned ON	Needed for the evaluation of
F00 $^{*)}$	Camera covered with cap	Value of dark offset, $w_{0,\text{off},j}$ Rate of thermally generated electrons, $r_{\text{th},j}$
F01 $^{**)}$	Laboratory lighting on	Physical area, shape and position (in pixels) of the individual light source modules (*required as reference)* and the trap.
F0	None	Dark.
F1	L_1	HDR index (see section 7.12), smearing, stray light, linearity, responsivity. Spatial distribution of the luminance of individual light source modules (*required as reference)*.
F2	L_2	
F3	L_3	
F4	L_4	
F5	L_5	
F6	L_6	
F7	L_7	
F1:7	$L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + L_7$	HDR index, stray light, linearity.

*) This acquisition is required for characterizing the parameters in the model at Eq. 2, need when this model is applied instead of applying the slower strategy of acquiring dark images for each measurement.

**) Acquisitions at this configuration F01 should be done at the beginning or at the end of the complete procedure, just before turning on or after turning off the light source modules.

6.2 External stray light procedure

The reference luminance source is **excluded** of the field of view of the DUT, except from L_1, which is located at the centre of the field of view, as shown in Figure 5. Remark: this configuration might i.e. be realized by moving the DUT closer to the source, but the source modules need to be realigned (tilted) to still illuminate the objective lens.
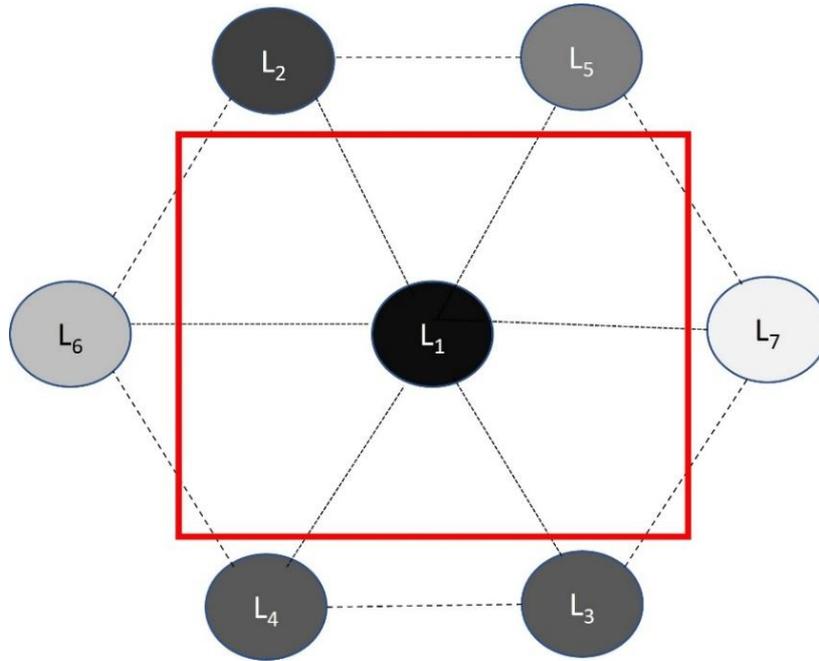
Figure 5: Spatial configuration of the high contrast source with respect to the field-of-view of the DUT (red rectangle), for the **external stray light procedure**. Note that the light source modules must be oriented to the objective lens of the DUT and overfill it.

The luminance measurements are carried out for the **luminance configurations** defined in Table 4.

Table 4: Luminance configurations for the **external stray light procedure**.

Configuration id.	Light source modules turned ON	Needed for evaluations of
E0	None	External stray light
E2	L_2	
E3	L_3	
E4	L_4	
E5	L_5	
E6	L_6	
E7	L_7	

7   Determination of empirical parameters

7.1   Preliminary definitions

In the following, we denote:

1. XN as the configuration.

2. $\mathbf{X_N}$, in bold, as the matrix representing the **acquisition** values obtained for the configuration XN.

3. **Acquisition** can be both:

   a. For systems providing direct response in DN at a given integration time: The values of the pixel's direct response divided by the integration time, in units of [DN·s^{-1}]. Note that by applying an high-dynamic-range (HDR) algorithm, the estimation of the acquisition are optimized for each pixel, regardless of the irradiance level at the pixel location.

   b. For systems previously adjusted in luminance by the provider: The values of the pixels in the image, in units of "adjusted cd·m^{-2}".

4. $\mathbf{X_N}$' as $\mathbf{X_N}$ after subtraction of the associated dark masurement.

5. $\mathbf{X_N}$'' as $\mathbf{X_N}$' after correction from non uniformity (PRNU), nonlinearity and drift by temperature.

Example:

F1 is the configuration, $\mathbf{F_1}$ is the acquisition matrix, and $\mathbf{F'_1} = \mathbf{F_1} - \mathbf{F_0}$.

7.2   Reference

The term **reference** means the exact position, size, shape, average luminance value and spatial distribution of each individual light source modules composing the reference source. The adequate determination of the reference is paramount for the characterization of the DUT.

1. **Position, size, shape**. These parameters are fully characterized, in terms of pixels, from the acquisition in configuration F01 (see Table 3). The pixels corresponding to the emission positions of the reference light source can be identified in $\mathbf{F_{01}}$. However, it is simpler to use acquisitions from configurations F1 to F7 (see

2.

3. Table 3) for this identification, applying a threshold equal to half of the maximum value. It must be noticed that this characterization is valid only for a given arrangement of both the reference light source and the DUT, that is, for a given characterization according to the fundamental procedure, where neither the position of the camera nor the source changes. This means that camera and sources **cannot be touched during the complete procedure**. Even the caps must be removed carefully to avoid disturbing the position of the individual source modules.

4. **Average luminance** of each individual light source i ($L_{V,i}$) across pixels containing emission positions. These values are provided by standard luminance measurements (e.g. by using a calibrated luminance meter) and should be provided with uncertainty.

5. **Luminance spatial distribution** of each individual light source. This distribution is obtained directly from the acquisitions at configurations F1 to F7 (see

6.

7. Table 3), under the assumption that the DUT is not affected by instrument response non-uniformity within the extent of the individual sources. If the average luminance of a source is measured over an area that is too small to be representative of the entire source, this parameter can be used to derive a correction factor accounting for spatial non-uniformities in source luminance.

8. **Matrix Reference, R**. This matrix represents the dark-subtracted image of the imaging measurement system that would be obtained in the absence of internal or external stray light, in the configuration F1:7 (see

9.

10. Table 3). Comparing this reference **R** with the actual dark-subtracted image $\mathbf{F'}_{1:7}$ allows for the evaluation and validation of stray light. The matrix is obtained as follows.
    a. Thresholding: The values in the matrices $\mathbf{F'}_1$ to $\mathbf{F'}_7$ that are below half of the maximum are set to zero. The resulting matrices ($\mathbf{F'}_{1,\text{thr}}$ to $\mathbf{F'}_{7,\text{thr}}$) are regarded as references for the individual sources.
    b. Composition: The matrix **R** is calculated as the sum of all the individual source reference matrices ($\mathbf{F'}_{1,\text{thr}}$ to $\mathbf{F'}_{7,\text{thr}}$).

7.3 Luminous responsivity

The luminous responsivity, s_V, of the DUT is defined as the average luminous responsivity across the sensor array, as $s_{V,L41}$ with reference to the CIE reference spectrum L41 [CIE 2023], under conditions without stray light, and in reference conditions where corrections for focus dependence and nonlinearity are not required. The CIE reference spectrum L41 is preferred because the DUT is intended to evaluate general lighting conditions under LED lighting. In the remaining parts of this report the symbol s_V for simplicity denotes the luminous responsivity with respect to the relative spectral distribution of the actual reference source, i.e. including the spectral mismatch correction in Equation (1).

The acquisitions from configurations F1 to F7 (see

Table 3) and the best estimation of the luminance of the individual light sources, $L_{V,i}$, which is obtained from an independent method (as a spot luminance meter or other type of luminance calibration), allows the luminous responsivity to be calculated, as:

$$s_{V,i} = \frac{\langle \mathbf{F}_i{''} \rangle_{k \in L_i}}{L_{V,i}} \tag{3}$$

where the subscript i denotes the individual source index, k is the index of an element (corresponding to a pixel) in $\mathbf{F''}_i$, and the expression $\langle \mathbf{X} \rangle_{k \in L_i}$ denotes the averaging operation on the values of the pixel region in $\mathbf{X}$ occupied by the individual source L_i. Each source i allows a best estimation of the luminous responsivity, s_V, to be calculated. In order to provide the best estimate of s_V, the individual light sources used in Eq. (3) should allow a signal-to-noise ratio (SNR) high enough to ensure that the uncertainty of the reference value is the dominating uncertainty . The values of $s_{V,i}$ obtained using different individual light sources, by Eq. (3), allow a definitive best estimation to be obtained.

The dependence of the measurement on temperature, pixel position (PRNU), nonlinearity and other effects, is given separately in the factors F_T, F_{NU}, F_{NL}, $\eta_{k,i}$, etc (see Eq. (1) and Table 1). This means that the responsivity s_V calculated at Eq. (3), corresponds to a value for which these corrections have already been considered. **This means that, before applying Eq. (3), these effects must be corrected in $\mathbf{F'}_i$.**

7.4   Dark signal

The variable $w_{0,\text{off},j}$ in Eq. (2) can be determined from acquisitions at configuration F00 at a very low integration time $t_{\text{e,j}} \to 0\ s$, and it is a fixed value for each pixel rendering the non-uniformity of the offset signal.

The product of variables $F_j \cdot r_{\text{th},j}$ is obtained also from acquisitions at the configuration F00 at different integration times, as the slope of $(w_j - w_{0,\text{off},j})$ with respect to the integration time. It is a fixed value for each pixel rendering the non-uniformity of the dark signal accumulated during the integration time interval.

It must be noticed that the dark signal, which has to be separated from the responsivity, depends on the sensor temperature. Therefore, the correction of the dark signal using calculated parameters needs similar conditions at characterization and measurement, or consideration of the sensitivity coefficient of the dark signal with the temperature.

An alternative for characterizing the dark signal is to obtain previously to the measurement the pixel-wise average and standard deviation of dark images captured at the integration times used in the measurement. It is important that, **when calculating the net signal by subtracting the dark signal, signals at the same integration time are subtracted**.

7.5   Noise

The noise of the response can be characterized by using the photon-transfer technique [Stark 1992], where the variance of w_j is evaluated for different values of w_j, covering the measurement range. This range can be covered by using different integration times or different luminances. The reference source described in this paper allows for both approaches to be studied. The linear fitting of the variance of w_j, $\sigma^2(w_j)$, with respect to w_j provides two empirical parameters, the readout noise (σ_{r}) and the factor F_j, which relates digital number, DN, or number of counts, to the readout electrons, as:

$$\sigma^2(w_j) = F_j w_j + \sigma_{\text{r}}^2 \qquad (4)$$

7.6   Internal stray light

The internal stray light, represented by the function, $\eta_{k,i}$, is related to the point spread function (PSF) of the instrument. The PSF represents how a point in the object is spread out in the image by diffraction and diffuse reflections (scattering) at optical components, and, consequently, can be used to describe how the direct irradiance on pixel k affects the signal at another pixel i.

The PSF can be measured by comparing the acquisitions at the configurations from F1 to F7 (see

Table 3) with the references of individual sources (from $\mathbf{F'}_{1,\text{thr}}$ to $\mathbf{F'}_{7,\text{thr}}$), obtained as described in Section 7.2. This comparison should allow empirical parameters to be found to describe the PSF.

The proposed procedure to follow is:

1) To select a simple model for the PSF, with a low number of parameters $(a_1,..a_N)$, in order to parametrize as PSF as PSF$(a_1,..a_N)$ = PSF(**a**). An example of model with three parameters, which gave satisfactory results for the tested instruments is:

$$PSF(d; a_1, a_2, a_3) = \frac{10^{a_1 \exp(-d/a_2)}}{1 + d^{a_3}} \qquad (5)$$

where the parameters (a_1, a_2, a_3) are always positive, and d is the distance to the position with the maximum value, in pixel units. Note that, when d is very large, the PSF tends to zero, and that when d tends to zero, the value of the PSF (its maximum) is 10^{a_1}, in this case. The value of the maximum is not important, since the relevant information is in the relative variation with respect to d. However, if the

PSF is applied for convolution or deconvolution, it usually normalized by its integrated value (integral equals to 1) to keep energy constant. In the model shown in Eq. (5), the numerator describes the relative variation of the signal for low values of d, whereas for high values the relative variation is dominated by the denominator.

2) To provide references for each configuration F1 to F7 ($\mathbf{F'}_{1,\mathbf{thr}}$ to $\mathbf{F'}_{7,\mathbf{thr}}$).

3) To minimize the error function: $\sum_k \chi_k^2 = \sum_k \frac{\{\mathbf{F'}_{c,k} - conv[\mathbf{F'}_{c,\mathbf{thr},k}, \mathrm{PSF}(\mathbf{a})]\}^2}{\mathbf{F'}_{c,k}}$ for the different configurations, from F1 to F7, where the subscripts c and k denotes configuration and pixel, respectively, and *conv* denotes the convolution function. Minimizing the error function means finding the optimal values of the vector of empirical values **a** for which the convolution of the image by the PSF better fits with $\mathbf{F'}_c$. In this case, a proper normalization factor must be selected, and it depends on the algorithm of convolution used. Usually, the PSF needs to be normalized to the sum or mean of its values, which makes the absolute value of the convolution dependent on the dimension selected by the PSF, that is the number of pixels included. In order to avoid this, a previous adjustment of the normalization factor is recommended, based on the idea that the values of $\mathbf{F'}_{c,k}$ and $conv[\mathbf{F'}_{c,\mathbf{thr},k}, \mathrm{PSF}(\mathbf{a})]$ have to coincide within the emission area of the source, where the impact of the PSF is very small. Regarding the dimension of the PSF recommended for minimizing the error function, this must be selected considering extension of the spread around the brightest source in the image, to make this dimension, expressed in pixels, a little larger. From the values of the parameters obtained with different configurations, it is possible to derive those values best representing the complete system and their uncertainty.

4) A different model for the PSF must be proposed if the residuals from the fitting still show some important tendency and cannot be considered as random.

5) Once the optimal PSF is obtained, it can be directly related to $\boldsymbol{\eta_{k,i}}$, since by this function represents exactly the PSF. In this case, the PSF must be normalized by the integrated value (at d = 0), and is given by:

$$\eta_{k,i} = \frac{PSF(d_{ki}; \mathbf{a})}{\int PSF(d_{ki}; \mathbf{a})} \qquad (6)$$

where d_{ki} denotes the distance in pixels between the pixels *k* and *i*.

The PSF should allow other quality indices [CIE 2021], such as Edge function, f_{25}, Stray light influence for negative contrast, f_{24}, and Size-of-source effect, f_{29}, to be obtained, by convolution of the optimal PSF with the reference images associated with each quality indices.

7.7 Smearing

[Note: The characterization of this effect only applies to CCD sensors, and must be done with the images in DN units at different integration times. The correction and its separation from (spectral dependent) non-linearity can be complex, and it is recommended to avoid, in measurement, the integration times for which smearing is noticeable.]

Smearing is the increase of signal in the pixels due to leakage of photoelectrons generated during the sensor readout time, outside of the integration time interval. The more comparable the readout time with respect to the integration time, the larger the relation between readout-time photoelectrons and integration-time photoelectrons, and more appreciable is the smearing. It is an effect occurring in CCD sensors, and it appears

as a column with unusual larger signal. The smeared columns are those with some highly irradiated pixels at some positions.

Smearing can be characterized from acquisitions at the configurations from F1 to F7 at different integration times, t_e. It must be determined from the observed relation between the increase of signal at non-irradiated pixels and the signal at irradiated pixels under different radiant exposures. The radiant exposure is directly related to the dark-subtracted signal, and can be quantified in terms of photoelectrons, counts or DN. The smearing must be calculated from the $w_{n,j}$ given in Eq. (2). The smeared signal in a pixel k from a pixel i can be expressed as:

$$\Delta_s w_{n,k,i} = s_{k,i} \left(\frac{t_{read}}{t_e} \right) w_{n,i} \tag{7}$$

where t_{read} is the readout time, and $s_{k,i}$ is an empirical parameter representing the leakage from pixel i to pixel k. Therefore, the function $\chi_{k,i}$ in Eq. (1) is defined as:

$$\chi_{k,i} = s_{k,i} \left(\frac{t_{read}}{t_e} \right) \tag{8}$$

Or, when the readout time is constant for any acquisition, as usually is, simply as:

$$\chi_{k,i} = \frac{s_{k,i}{}'}{t_e} \tag{9}$$

Note that the smear on a pixel is only produced at the pixels in the same column, and that it is constant for all pixels in that column if there is not temporal modulation of the light. Therefore, we can write:

$$\chi_{k,i} = \begin{cases} \dfrac{s'}{t_e}, \text{if pixels } i \text{ and } k \text{ are in the same column} \\ \\ 0, \text{otherwise} \end{cases} \tag{10}$$

Typically, the readout time, t_{read}, can be estimated from the frame rate. For instance, for a frame rate of 40 fps (frame per second), a readout time of 1000 ms / 40 fps = 25 ms is obtained. Values in the order of 10^{-5} are typical for $s_{k,i}$.

For measurements, it si recommended to avoid conditions for which smear is not negligible, by determining and limiting the minimum allowed integration time for acquisitions. This, however, for a given responsivity, reduces the maximum luminance that can be measured by the device configuration, i.e. altered by the objective lens, aperture setting or neutral density filter.

The performance of ILMDs in terms of error due to the smear is quantified in CIE 244:2021 with the quality index "Influence of smear", f_{26} [CIE 2021].

7.8 External stray light

The external stray light can be characterized from acquisitions at the configurations from E1 to E7.

E'$_1$… **E'$_7$** represent the increase on the signal due to the external stray light (ζE_{bg}). This can be regarded as proportional to the illuminance (E_V) on the DUT from outside its FOV, which can be calculated as:

$$E_V = L_V A / d^2 \tag{11}$$

where L_V is the luminance of the source, A is its area, and d the distance between the source and the DUT.

Therefore, for an arbitrary configuration Ei, where the objective lens is irradiated by the light source L_i, it is obtained that:

$$\zeta = \langle \mathbf{E'_i} \rangle d_i{}^2 / L_{V,i} A_i \qquad (12)$$

where $\langle \mathbf{E'_i} \rangle$ is the average of the matrix $\mathbf{E'_i}$. A representative value for the device is calculated as the average of the values ζ obtained for the different configurations.

ζ is a characteristic specifically of the camera, whereas E_{bg} has illuminance units and depends on the lighting environment. At measurement conditions, E_{bg}, produced at the camera position by light sources out of the scene to be measured, needs to be evaluated with an illuminance meter, by blocking the light from the sources within the field of view of the DUT camera.

The performance of ILMDs in terms of error due to the external stray light is quantified in CIE 244:2021 with the quality index "Effect of surrounding field", f_{23} [CIE 2021].

7.9 Photo-response non-uniformity, PRNU

[Note: The reference source cannot be used for a pixelwise characterization of the PRNU, which would require a homogeneous light source within the complete field of view of the instrument, unless a scanning method is additionally implemented].

This variable can be verified using the reference source proposed in the HiDyn project. For this characterization, it is necessary to provide the same luminance condition for all pixels, simultaneously (flatfielding) or subsequently (by scanning). The latter would be performed using a nodal point head of a tripod, where deviations due to a small angular dependence of the source modules luminance will be avoided.

The flatfielding is usually carried out using the exit port of an integrating sphere. The PRNU might change with the focus configuration or with the neutral density filter and must be evaluated for the different configurations for operation. However, the exit port of an integrating sphere in not large enough to irradiate under the same conditions all pixels from long distance. One solution is to keep always the measuring system to be evaluated very close to the exit port even when the exit port is not focused [Sáez 2025]. The factor F_{NU} is obtained as the relative response of the pixels under identical conditions, normalized to the mean value of the pixels for which the luminous responsivity was characterized. The normalization factor is imposed by the characterization of s_V. After normalization, the average of F_{NU} across the pixels used for the characterization of s_V must be 1.

This kind of characterization is important, for instance, for evaluating the glare form non-uniform luminaires, according to the procedure recommended by CIE 232:2019, "Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance" [CIE 2019].

7.10 Spectral mismatch correction, SMCF

[Note: The reference source alone cannot be used for this characterization. It is required spectral analysis of the sources in the scene and the relative spectral responsivity of the instrument. Therefore, the characterization of this effect is complex, and its correction, not specific to an HDR scene, is very time consuming.]

The spectral mismatch correction requires the determination of the relative spectral responsivity of the imaging system, and the spectral power distribution of the light sources evaluated (obtained by standard procedures) and the spectral power distribution of the CIE reference spectrum L41 [CIE 2023]. The spectral mismatch correction factor F_{SM} is calculated as recommended by CIE S 023/E:2013 [CIE 2013].

This is a scene-dependent correction, meaning that different spectral mismatch corrections are applied according to the spectra of the light sources in the scene. As a consequence, this correction does not need to be done pixelwise, but once the average luminance of the different light sources in the scene has been calculated by integrating the luminance values of the pixels. However, the factor F_{SM} is given explicitly in Eq. (1) to express that this factor depends on the pixel through the position of the light sources in the scene.

The spectral distribution of the radiance of the different sources in the scene is sometimes unknown. In such cases, F_{SM} needs to be estimated from typical relative spectral power distributions (SPD). For secondary sources in a high contrast scene this is more complex since the spectral distribution requires the bidirectional reflectance distribution function (BRDF) of the reflecting surface and multiple reflections within the scene might be considered. The uncertainty of F_{SM} will depend strongly on the goodness of the approximation that is considered.

7.11 Non-linearity

The nonlinearity with respect to the photoelectrons (directly related through the conversion factor to the net signal, in counts or DN, as typical units from imaging systems), as given in Equations. (1)-(2), can be calculated from the acquisitions at the configurations from F0 to F7 at different integration times. It would allow to calculate the relative variation of the ratio (photoelectrons) / (integration time) with respect to the photoelectrons over a high dynamic range. Since, for a linear detector, this ratio should be constant for a fixed luminance, its variation represents the factor of nonlinearity with respect to the photoelectrons ($F_{NL,j}$). In addition, the evaluation of the relative variation of this ratio with respect to the integration time allows the usable integration time to be determined. In some cases, as when there is smearing, the correction of this last effect cannot be corrected. In this case, for very short integration times (typically lower than 1 ms), it can be observed that the nonlinearity function raises at low-count values compared to the functions determined with longer integration times.

When the integration time is not accessible, and the response of the camera is related directly to the ratio (photoelectrons / integration time), this variable can be estimated from the acquisitions at the configurations from F0 to F7, by comparing with the reference. The variation of the relative luminance responsivity for different luminance values, calculated for the light source L_i as

$$s_{\mathrm{V,i,rel}} = \frac{\mathbf{F}_i{}'}{F_{\mathrm{NU}} L_{\mathrm{V,i}}}, \tag{13}$$

determines the residual error due to the nonlinearity. Note that the correction factor for the non-uniformity F_{NU} needs to be considered, otherwise this source of error would be quantified incorrectly as part of the non-linearity.

7.12 Achievable dynamic range (HDR indices)

In this report the ground-truth luminance (L_{GT}) is defined as the luminance obtained when the light source is not surrounded by other light sources producing internal stray sight which might affect its measurement. The modified luminance (L_m) is defined as the luminance obtained when the light source is surrounded by other light sources producing internal stray might which affects its measurement.

By comparing the reference $\mathbf{R}$ with $\mathbf{F}'_{1:7}$, it is possible to describe the relation between the decades of the ground-truth luminance (L_{GT}) in the scene and the decades of the modified luminance (L_m) by each measurement system.

This relation depends on the number of decades: the fewer the decades to be measured, the lower the impact of stray light in reducing the dynamic range of the acquisitions. The relative reduction of decades, ΔD, is defined as:

$$\Delta D = \frac{|\Delta \log_{10}(L_{\mathrm{GT}}) - \Delta \log_{10}(L_{\mathrm{m}})|}{\Delta \log_{10}(L_{\mathrm{m}})}, \tag{14}$$

where $\Delta \log_{10}(L)$ denotes the number of decades within a given range, and this is calculated as the difference between the decimal logarithms of minimum and maximum luminances within the range, as:

$$\Delta \log_{10}(L) = \log_{10}(L_{\mathrm{max}}) - \log_{10}(L_{\mathrm{min}}) \tag{15}$$

The relative reduction of decades, ΔD, depends on the number of decades in the luminance scene. It was tested that ΔD increases exponentially with respect the number of decades [Ferrero 2025(2)], and can be empirically modelled as:

$$\Delta D = f_{\mathrm{HDR},1} \cdot 10^{D_{\mathrm{GT}} f_{\mathrm{HDR},2}}, \tag{16}$$

where:

- D_{GT} denotes the GT number of decades in the scene and is calculated as:

$$D_{\mathrm{GT}} = \Delta \log_{10}(L_{\mathrm{GT}}) \tag{17}$$

- $f_{\mathrm{HDR},1}$ and $f_{\mathrm{HDR},2}$ are empirical parameters.

Both $f_{\mathrm{HDR},1}$ and $f_{\mathrm{HDR},2}$ are empirical parameters whose values are determining by fitting the Eq. (16) to the experimental data obtained for ΔD at different values of D_{GT}.

The calculation of ΔD through Eq. (14) can be applied to any other luminance distribution, as long the GT is known, i.e. by reference measurements using a conventional spot luminance photometer. However, the result can depend strongly on this distribution for a given imaging system. For instance, ΔD would increase toward lower distances between the brightest and the dimmest sources, or with the size of the brightest source. This report proposes to restrict the calculation of $f_{\mathrm{HDR},1}$ and $f_{\mathrm{HDR},2}$ to the hexagonal distribution defined by **R**, with:

- The dimmest light source always at the center.

- Light sources of identical sizes.

- Light sources small with respect to the complete image.

- Light sources large with respect to the pixel, i.e. many pixels.

- For all sources, the same distance to the dimmest source (between 1/4 and 1/3 of the largest side of the image).

These restrictions must minimize the variation of the obtained $f_{\mathrm{HDR},1}$ and $f_{\mathrm{HDR},2}$ with slightly different luminance distributions.

7.13 Sensitivity coefficients

The previous characterizations require an evaluation of the repeatability (by multiple repetitions) and the provision of the corresponding uncertainty for the different variables or empirical parameters. This would allow the sensitivity coefficients to be calculated, as it is shown in [Ferrero 2025]. The formal expression of the sensitivity coefficients is derived as recommended by the *Guide to the expression of uncertainty in measurement* (GUM) [GUM 2008] from Eqs. (1) - (2).

7.14 Performance for measuring glare or obtrusive light indices

The reference source can be used for determining the performance of a given DUT for measuring typical indices defined for evaluating glare or obtrusive light, which are functions of the luminance, positions and subtended solid angles of the light source within the field of view, and also of the background luminance. In these cases, the configuration defined above (Table 2) is not used anymore, but configurations providing a simplified version of representative scenes to be evaluated in the field. The performance is evaluated experimentally by comparing the index calculated by using the reference value corresponding to that configuration, as above defined, and the index calculated from the measurement of the selected configuration.

Alternatively, this performance can be simply calculated by estimating the uncertainty in the measurement of the indices. To estimate this uncertainty, it is taken into account the better estimation and uncertainty of the light sources and the background luminances, which are obtained from the measurement models in Equations.

(1) - (2), as recommended by the *Guide to the expression of uncertainty in measurement* (GUM) [GUM 2008], and after carrying out the procedures described in this document.

7.15 Verification

To verify that the proposed characterization based on individual sources allows the effect by internal stray light to be explained when a different scene (with very different and simultaneous luminance levels) is evaluated, the image $\mathbf{F'}_{1:7}$ is compared to the convolution of $\mathbf{R}$ with the characterized PSF, conv[$\mathbf{R}$, PSF($\mathbf{a}$)], denoted here as $\mathbf{F'}_{1:7,s}$, where the subscript 's' denotes 'synthetic'. The comparison is evaluated in terms of χ^2_k (see Section 7.6, item 3, for definition).

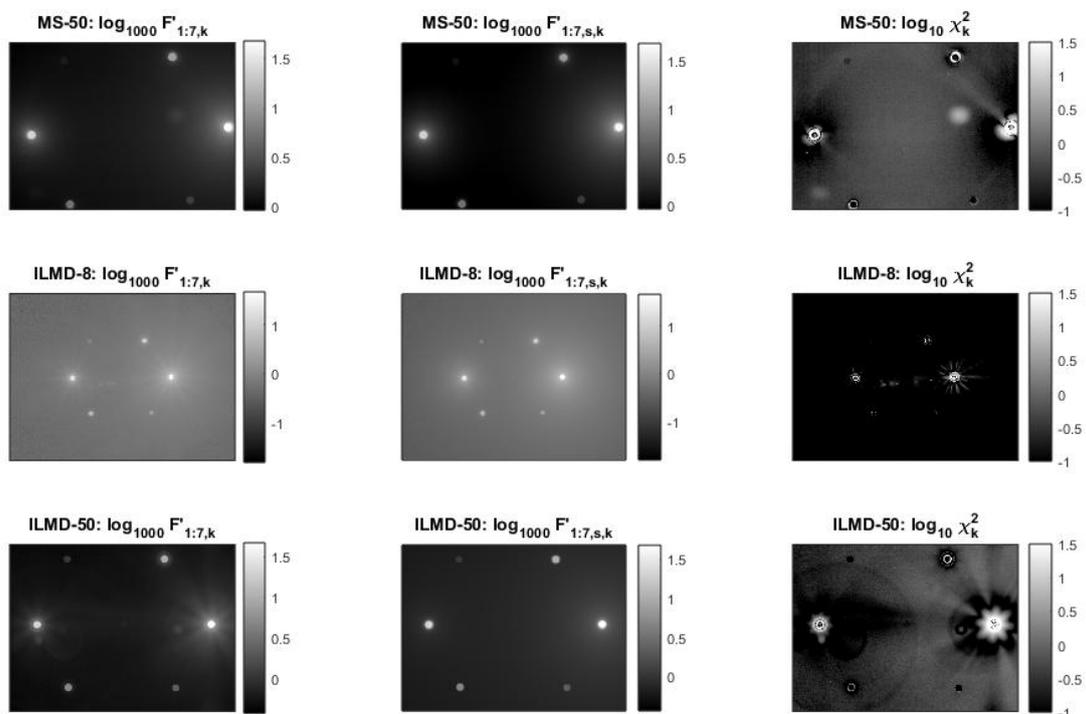The verification for the studied systems is illustrated in Figure 6.

Figure 6: Examples of verification of HDR imaging luminance measurements with three different imaging measurement systems (MS-50, ILMD-8 and ILMD-50, in different image rows). The first image column represents the logarithm in base 1000 of $\mathbf{F'}_{1:7}$, the second image column represents the logarithm in base 1000 of $\mathbf{F'}_{1:7,s}$, (conv[$\mathbf{R}$, $\mathbf{PSF}(\mathbf{a})$]), and the third image column represents χ^2_k.

8 References

[CIE 2013] CIE S023/E:2013 Characterization of the Performance of Illuminance Meters and Luminance Meters, Joint ISO/CIE International Standard.

[CIE 2019] CIE 232:2019 Discomfort Caused by Glare from Luminaires with a Non-Uniform Source Luminance. DOI: 10.25039/TR.232.2019.

[CIE 2021] CIE 244:2021 Characterization of Imaging Luminance Measurement Devices (ILMDs). DOI: 10.25039/TR.244.2021.

[CIE 2023] CIE 251:2023 LED Reference Spectrum for Photometer Calibration. DOI: 10.25039/TR.251.2023.

[GUM 2008] Evaluation of measurement data — Guide to the expression of uncertainty in measurement, JCGM 100:2008.

[Ferrero 2025] A. Ferrero *et al.*, "Luminance measurement model for high-dynamic-range imaging systems," in preparation, to be submitted to Optics Express before the end of 2025, as an outcome of this project.

[Ferrero 2025(2)] A. Ferrero *et al.*, "Method for the photometric characterization of high-dynamic-range imaging measurement systems with a high contrast reference light source," in preparation, to be submitted to Optics Express before the end of 2025, as an outcome of this project.

[HiDyn 2025] Report describing the design, development and technical specification of a type of high-contrast-luminance reference standard (covering at least 6 orders of magnitude), including the determination of luminance with an expanded uncertainty no larger than 1 % for the brightest source and no larger than 2 % for the dimmest one (Deliverable 1), 21NRM01 HiDyn, 2025.

[Saez 2025] A. Sáez and A. Ferrero, "Characterization of photoresponse non-uniformity and non-linearity of multispectral cameras for radiance and luminance measurements," in CIE's Midterm Meeting 2025, (2025).

[Stark 1992] Stark, B., Noelting, B., Jahn, H., & Andert, K. (1992). Method for determining the electron number in charge-coupled measurement devices. *Optical Engineering*, *31*(4), 852-856.