# NEAR-FIELD GONIOPHOTOMETRY: A METROLOGICAL CHALLENGE

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**Abstract:** Near-field goniophotometry, which provides luminance distribution of a light source, is a very suitable tool for generating ray data needed for the design of modern luminaries. International efforts are currently being put into elaborating guidelines for the measurement procedures and traceability of near-field goniophotometric measurements. In order to support the traceability of such measurements, PTB has recently installed a near-field goniophotometer. The first results of near-field measurements carried out with this goniophotometer are presented, and the problems of establishing the traceability of these measurements are also shown in this paper.

## 1. INTRODUCTION

In the last few years, near-field goniophotometry has proved to be a very suitable tool for measuring the luminance distribution $L(x_\mathrm{S}, y_\mathrm{S}, z_\mathrm{S}, \vartheta_\mathrm{E}, \varphi_\mathrm{E})$ of a light source. These measurements are used for generating ray data (“ray files”), which are commonly employed for optical simulation tools (ASAP, Zemax, etc.) for the design of modern luminaries, e.g. headlamps which use LEDs as light sources [1, 2, 3].

Unlike a traditional far-field goniophotometer, a near-field goniophotometer employs a CCD-based imaging photometer as a detector which offers some advantages: (i) a near-field measurement can be carried out at any distance from the light source, (ii) the starting point and the direction of the rays in the emitted radiation of the light source (near-field model) can be determined accurately and (iii) far-field quantities of a light source can be determined from near-field goniophotometrical measurements; e.g., the luminous intensity distribution and the total luminous flux.

Although near-field goniophotometry presents the advantages mentioned above, it also has some technical challenges: a very high amount of measurement data is generated which requires vast computer resources for its evaluation, and until now, such measurements have not had a well-defined traceability. Therefore, at PTB, a near-field gonio-photometer has recently been installed. It will be used to evaluate light sources for their suitability as transfer standards, especially those of solid state types, like LEDs or OLEDs.

## 2. MEASUREMENT PRINCIPLE OF A NEAR-FIELD GONIOPHOTOMETER

The determination of the total luminance distribution of a light source involves the measurement of the luminance distribution for all directions in which light is emitted. The luminance distribution is an intrinsic characteristic of the light source/luminous object which describes the variation of the luminance of the area elements $\mathrm{d}A(x_\mathrm{S}, y_\mathrm{S}, z_\mathrm{S})$ of the object surface, that is,

$$L(x_\mathrm{S}, y_\mathrm{S}, z_\mathrm{S}, \vartheta_\mathrm{E}, \varphi_\mathrm{E}) = \frac{\mathrm{d}\Phi}{\mathrm{d}A(x_\mathrm{S}, y_\mathrm{S}, z_\mathrm{S}) \cdot \cos\vartheta_\mathrm{E} \cdot \mathrm{d}\Omega(\vartheta_\mathrm{E}, \varphi_\mathrm{E})}, \quad (1)$$

where $\mathrm{d}\Phi$ is the luminous flux portion, $\mathrm{d}\Omega(\vartheta_\mathrm{E}, \varphi_\mathrm{E})$ is the solid angle element in the direction $(\vartheta_\mathrm{E}, \varphi_\mathrm{E})$ and $\vartheta_\mathrm{E}$ is the angle between the normal $\overline{\mathrm{d}A}$ of the surface area and the direction of the solid angle element (see Figure 1).

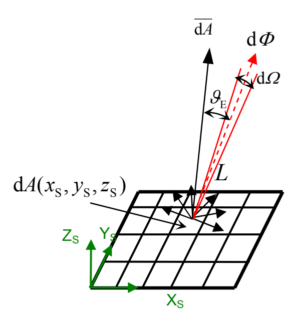


***Figure 1.*** *Representation of the luminance distribution of a luminous surface.*

For these measurements, a near-field gonio-photometer uses a special camera (luminance measuring camera) which captures the luminance image, i.e. the central projection of the luminance distribution, of the light source for all directions in which light is emitted. The measurements are carried out by moving the measuring camera with the mechanical system of a goniophotometer on an imaginary spherical surface around the light source to be measured (see Figure 2). Each pixel ($i$, $j$) in the luminance image defines a solid angle element $d\Omega_{Pixel}(i, j)$, and an area element $dA(\vartheta, \varphi)$ that defines a luminous flux portion $d\Phi(i, j)$. These luminous flux portions can be regarded as ray data. If the camera position $\{\vartheta_c, \varphi_c\}$ is known, the image coordinates $\{x', y'\}$ in the CCD-matrix can also be determined (see Figure 3). For cameras with distortion-free objectives, this relation can be given according to equation (2). Thus, using this information, the image data can be converted into rays with respect to the goniometer coordinate system (device coordinates).

$$\vartheta_C(i, j) = \arctan\left(\frac{\sqrt{x'^2 + y'^2}}{f'}\right) = \arctan\left(\frac{\sqrt{(i\cdot\Delta x_{Pixel})^2 + (j\cdot\Delta y_{Pixel})^2}}{f'}\right)$$

$$\varphi_C(i, j) = \arctan\left(\frac{y}{x}\right) = \arctan\left(\frac{j\cdot\Delta y_{Pixel}}{i\cdot\Delta x_{Pixel}}\right) \qquad (2)$$

A ray can be interpreted as a vector, the norm of which is the luminous flux portion $d\Phi$. Thus, from equation (1), the discrete luminous flux portion is obtained as,

$$\Delta\Phi(x, y, z, \vartheta, \varphi) = \int_{\Delta\Omega} \int_{\Delta A} L(x, y, z, \vartheta, \varphi)\cdot dA \cdot \cos\vartheta \cdot d\Omega \qquad (3)$$

If the radiant field is considered for the direction ($\vartheta_S$, $\varphi_S$), the luminous intensity distribution $I(\vartheta, \varphi)$ of the light source in this direction is obtained as,

$$I(\vartheta_S, \varphi_S) = \int_A L(x_S, y_S, z_S, \vartheta_S, \varphi_S)\, dA_P \qquad (4)$$

where $dA_p$ is the area element projected onto the direction ($\vartheta_S$, $\varphi_S$). Here, it should be noted that for the case of discrete notation by ray data, all rays going into one direction must be added up. That is,

$$I(\vartheta_k, \varphi_l) = \frac{\sum_{x,y,z} \Delta\Phi(x_S, y_S, z_S, \vartheta_S, \varphi_S)}{\Delta\Omega(\vartheta_k, \varphi_l)} \quad \forall\, \vartheta_S, \varphi_S \in \Delta\Omega(\vartheta_k, \varphi_l)\,. \qquad (5)$$

The total luminous flux resulting from the ray data is then given as,

$$\Phi_V = \iint_{A,\Omega} L(x, y, z, \vartheta, \varphi)\cdot dA \cdot \cos\vartheta \cdot d\Omega\,, \qquad (6)$$

which is equivalent to the sum of all the discrete ray data. That is,

$$\Phi = \sum_{x_S, y_S, z_S} \sum_{\vartheta_S, \varphi_S} \Delta\Phi(x_S, y_S, z_S, \vartheta_S, \varphi_S)\,. \qquad (7)$$

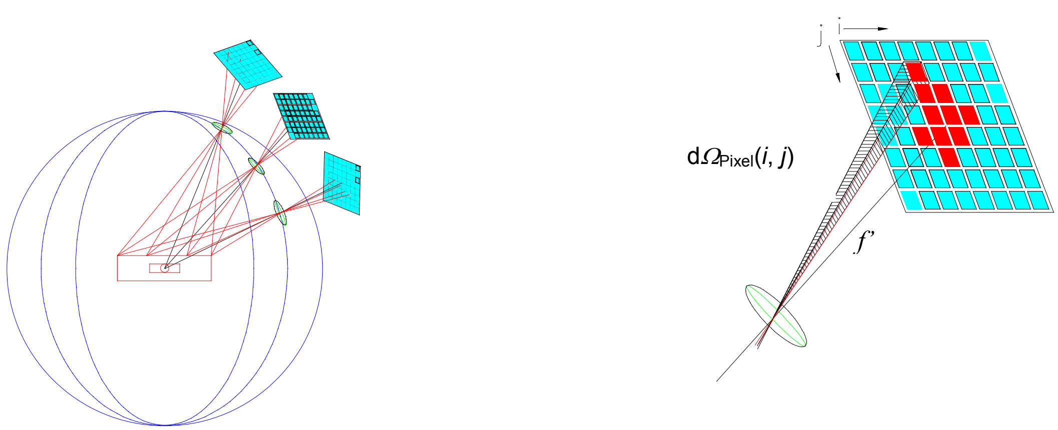


***Figure 2.*** *Principle of a near-field goniophotometric measurement.*

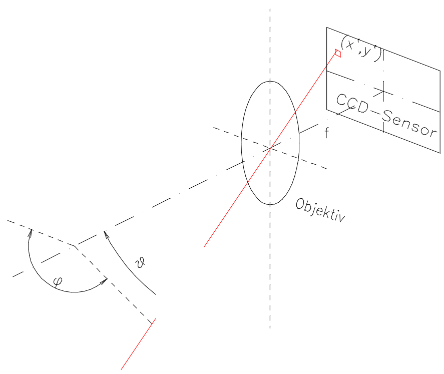


***Figure 3.*** *Camera-coordinate system.*

## 3. NEAR-FIELD GONIOPHOTOMETER AT PTB

PTB developed a special setup for LED goniophotometry to be able to measure all kinds of LEDs under far-field conditions as well as under all the different conditions given in the CIE document CIE 127:2007 [4]. Recently, this facility has been expanded by adding a luminance measuring camera for carrying out near-field goniophotometric measurements (see Figure 4). Unlike typical near-field goniophotometers, in this setup the luminance camera is maintained at a fixed position, while the LED is moved over the angles $\{\vartheta, \varphi\}$ during the measurement. The luminance measuring camera is equipped with several objectives which allows the capture of measurement objects (e.g. organic LEDs) with a diameter of up to 100 mm. Spectrally resolved near-field measurements can also be carried out by adding a badpass filter to the luminance measuring camera. The ray data are determined by using commercial software [5]. However, in order to support the versatility of this facility, it is planned to

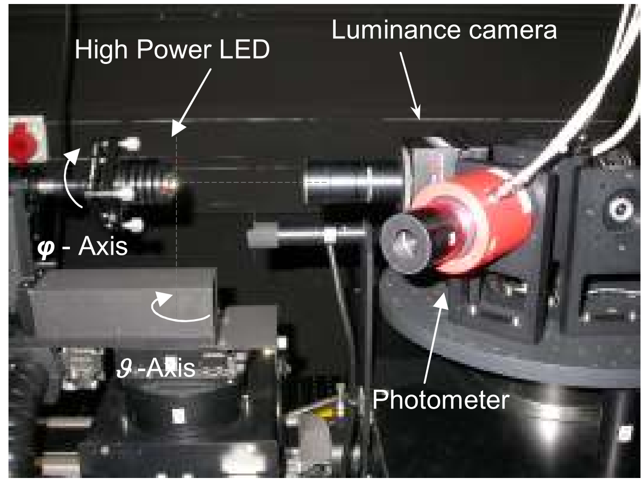


***Figure 4.*** *Far- and near-field goniophotometer at PTB.*

implement newly built software modules of our design for the evaluation of the ray measurement data. By substituting a spectroradiometer for the camera, with its fiber input mounted on the rotary stage (see Fig. 4) adjacent to the photometer, the light source can also be characterized spectrally in the far field.

## 4. RESULTS

Figure 5 shows the luminance image (luminance distribution) of a high-power LED Luxeon Rebel for the direction $\{\vartheta=0, \varphi=0\}$. The LED is operated at a photocurrent $I_f$= 300 mA, a forward voltage $V_f$ = 3.02 V and a chip temperature $T_{chip}$= 31°C. As expected, high luminance levels are observed (see Figure 5c). The luminance intensity distribution obtained from the ray data as well as a set of rays generated from the luminance distribution measurements are shown in Figure 6.

a) b) c)

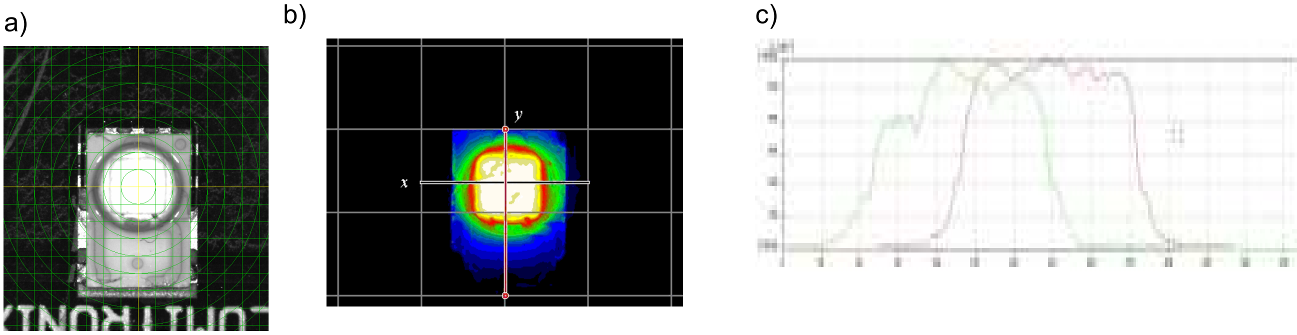


***Figure 5.*** *(a) LED picture, (b) luminance image and (c) luminance x- and y- of the luminance distribution of a high-power LED Luxeon Rebel.*

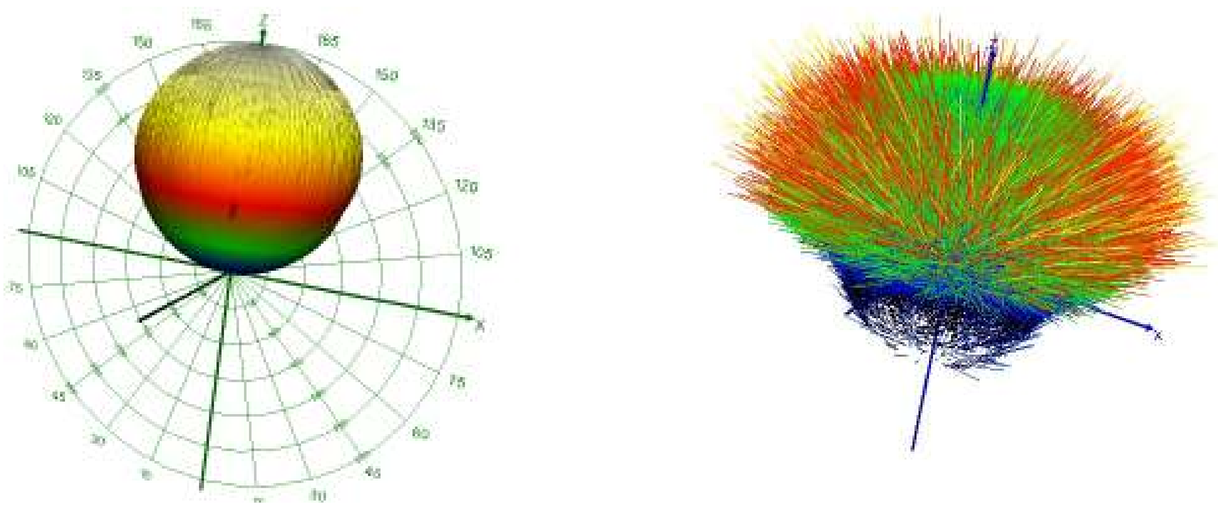

***Figure 6**. Left: luminance intensity distribution obtained from the ray data; right: radiation characteristics represented by ray data.*

For convenience, only 1 million rays are shown. Observing the measured luminance intensity distribution of the LED, it is evident that it closely follows that of a perfect Lambertian emitter.

## 5. TRACEABILITY OF A NEAR-FIELD GONIOPHOTOMETER

The traceability of near-field goniophotometric measurements is the subject of current discussions in the CIE[1] and DIN[3]. Members of the technical committees TC 2-62 (CIE) and FNL3 (DIN) are working together on the preparation of a recommendation on methods for the characterization and calibration of imaging-photometer-based near-field goniophotometers. PTB is one of the first National Metrology Institutes (NMI) to have such a measurement system installed to actively support the work on norms and written standards, to establish this measurement method as well as to realize the traceability chain for such measurements.

The measurands obtained from near-field goniophotometric measurements can be divided into two groups: ray data (luminance distribution $L(x, y, z, \vartheta, \varphi)$) which are discrete and position resolved; as well as integral quantities like the luminous intensity distribution $I(\vartheta, \varphi)$ and the total luminous flux $\Phi_v$.

Transfer standards (light sources) calibrated with respect to national standards traceable to the SI unit candela can be used to establish a traceability chain for the integral measurands ($I(\vartheta, \varphi)$ and $\Phi_v$). However, it is much more complicated to realize the traceability of ray data obtained by the luminance distribution measurements $L(x, y, z, \vartheta, \varphi)$ of a light source. Here the measured quantity is four-dimensional; it depends on the starting $\{x, y, z\}$ position and direction $\{\vartheta, \varphi\}$ of the rays. Furthermore, the total data field is formed by about $10^5$ to $10^9$ rays.

An additional problem to be solved is that luminance cameras are usually calibrated separately against a luminance standard used as a light source under fixed and defined reference conditions [6]. But there are a lot of camera parameters, which contribute to the measurement uncertainty under real conditions and, hence, the measurements are not yet traceable. Straylight, the surrounding area, homogeneity and other parameters which depend on the light source being measured, have an unpredictable influence on the measurement uncertainty at the moment.

## 6. SUMMARY

Near-field goniophotometry presents remarkable advantages versus the traditional far-field goniophotometry. It provides much more information about the luminous flux emitted by a light source; i.e.

[1] CIE Commission Internationale de l'Eclairage (http://cie.co.at)
[3] DIN Deutsches Institut für Normung e.V. (http://www.de)

the starting point and the direction of the rays within the emitted flux. Using this information, ray data files are generated which are used for the design of modern luminaries. The traceability of such measurements, however, poses a great challenge at the moment. This is mainly due to the fact that currently there are no well-defined standards and calibration methods available for luminance distribution measurements as well as for generating ray data. For this purpose, PTB has established a near-field goniophotometer. The first measurements have been presented. It is planned to develop software of our own design for generating ray data as well as to validate the system by means of comparisons against far-field measurements and the estimation of the measurement uncertainty.

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