EMRP ENG05 Metrology for Solid State Lighting

D2.3.3 Report on Model for Illuminance produced by LEDs as a function of distance

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Introduction

The purpose of this activity was to study goniometrical aspects of LEDs to develop a model for the illuminance produced by LEDs as a function of distance. High brightness as well as high power LEDs with different angular half width and spectral distribution were selected. Selected LEDs are summarized in Table I and II:

Table I

High brightness LEDs HB Hebei I.T

LED	LED type	No. of LEDs	Angular half width (nominal)/°	I_f / mA
HBW30(*)	White	2	30	20
HBW60	White	2	60	20
HBB40	Blue	2	40	20
HBG40	Green	2	40	20
HBR40	Red	2	40	20
HBR20	Red	2	20	20

Table II

High Power LEDs : Cree XR-C Lamp and Lumileds Luxeon

LED	LED type	No. of LEDs	Angular half width (nominal)/°	I_f / mA
XRCCW(*)	Cool white	2	90	350
XRCNW	Neutral white	2	90	350
XRCW	White	2	90	350
XRCWW-	Warm white	2	90	350
XRCBLU-	Blue	2	90	350
XRCRED-	Red	1	90	350
XRCGRN	Green	1	90	350
LXML-PWW	Warm white	2	60	350
LXML-PWC	Cool white	1	60	350

Measurement setup

Two different setups have been used in this activity. In a first stage the low uncertainty Spanish Goniospectrophotometer (GEFE) [1] (initially intended for the absolute measurement of BRDF of materials) was adapted to measure the angular and spectral distribution of selected LEDs (see fig 1).

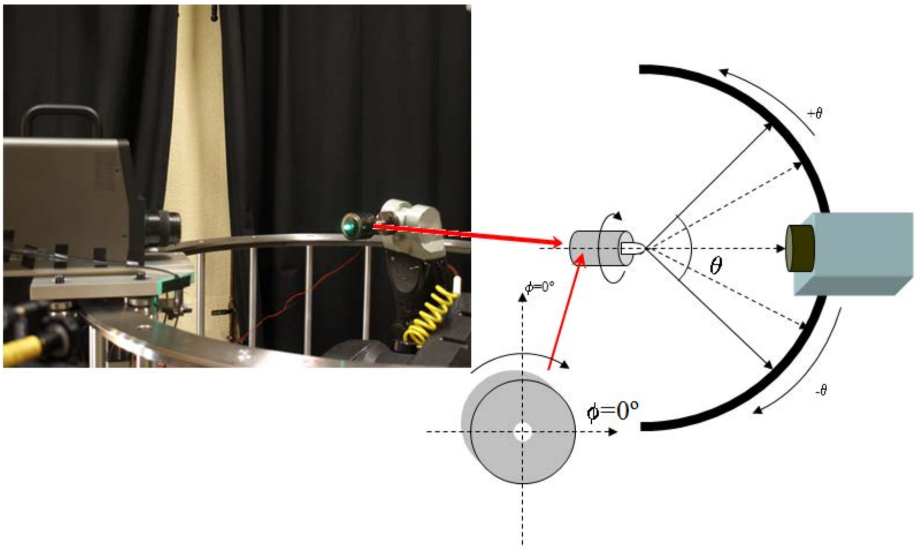


Figure 1. Setup used to measure the angular distribution of LEDs by means of the low uncertainty Spanish Gonio-spectrophotometer (GEFE).

The LED was located in the robot arm of the positioning system in the center of the reference plane (X,Y,Z). Illuminance was measured with a Konica Minolta CS-2000 spectroradiometer with illuminance accessory attached. Different test sockets have been designed to permit correct alignment of the mechanical axis of LEDs with different packages. Crossing point of two lasers beams placed at 45° and -45° relative to the horizontal angle θ = 0° was used as alignment system. With this setup, a fixed distance of 383,7 mm between LED and spectroradiometer was used. Following CIE recommendations [2] the tip of the LED is used as the reference point for distance assesment.

Four different values of ϕ (0°, 45°, 90° and 135°) were used in the measurements, whereas the horizontal angular range (θ) covered was variable, depending on the divergence angle of every LED. Intervals of 10 % of the nominal value of the divergence angle were used for each of the measurements.

Regarding the high-power LEDS, a constant current of 350 mA and a temperature of 25 °C were used. LED- 850 Test Adapter from Instrument Systems and TEC Source 5300 from Arroyo Instruments were used as temperature controllers.

Constant current of 20.0 mA was used for the high brigtness LEDs. A calibrated standard resistance (R = 1 Ω) was used to control the current intensity. Electrical parameters were monitored with multimeters HP 3478 A and Agilent 34401 A.

As mentioned, this setup does not allow change the distance between the LED under measurement and the spectroradiometer. In a second stage illuminance measurements as a function of distance, using a photometer, have been performed on a 3 m optical bench (see fig. 2). Measurements were made at forty distances in the distance range of 25 – 1500 mm, with variable intervals. CIE A (d = 316 mm) and B (d= 100 mm) conditions were always recorded.

The photometer was mounted on a rail carrier and the tested LEDs were placed, one by one, at the other end of the optical bench. Following CIE recommendations, the mechanical axis of the LED was aligned perpendicular to the receiving aperture of the photometer.

As photometer, a commercial standard photometer, temperature stabilized, manufactured by LMT Lichtmesstechnik GmbH was used. The photometer has a circular entrance aperture with an area of 100 mm^2. The photometer has a planar diffuser behind the aperture to improve its angular responsivity. The illuminance responsivity of the photometer has been previously calibrated by direct comparison with one standard photometer of CSIC. For the determination of the spectral mismatch correction factor, the relative spectral responsivity of the photometer was measured with the reference system of CSIC.

To obtain angular distributions at various distances, the LEDs were mounted on a turntable. Complete recording on θ, ϕ and distance was very time consuming; so for this system, intervals of 30 % of the nominal value of divergence angle has been used for horizontal angular range θ. It has to be mentioned also, that due to the mechanical construction of the system, the horizontal angular range, θ, is limited to $-40° \leq \theta \leq 40°$.

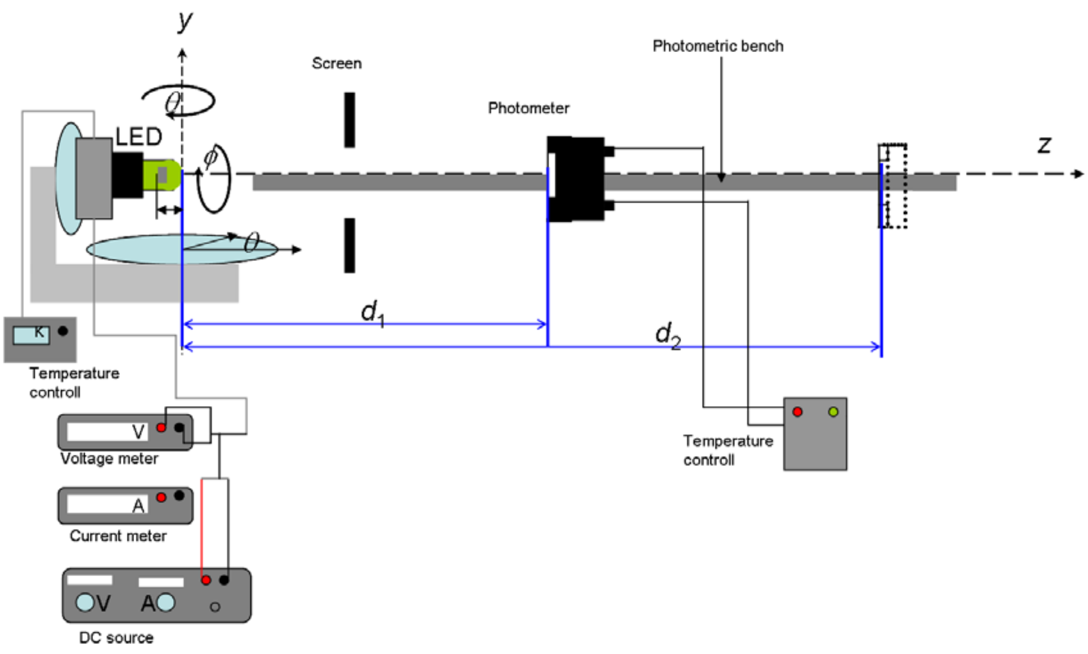
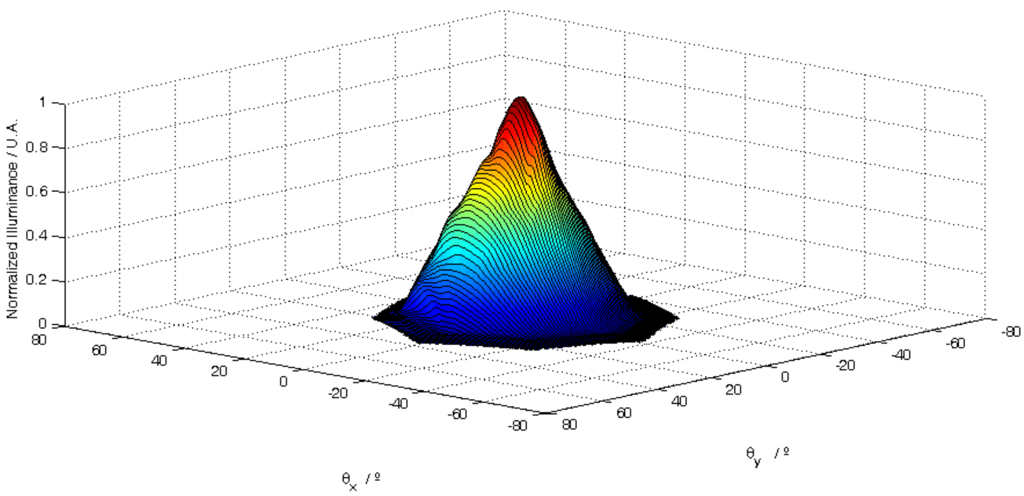


Figure 2. Scheme of the optical bench used in the illuminance measurements as a function of distance.

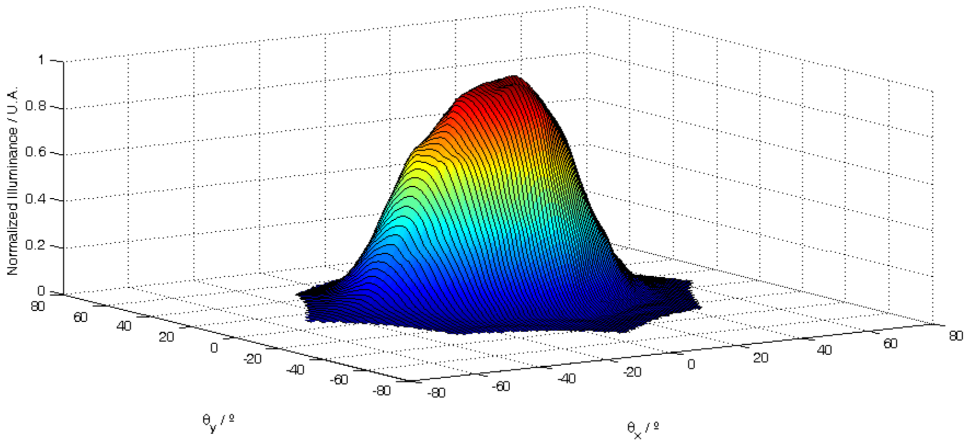
Measurement results

We present in the following some examples of the results obtained in the measurements from both setups [3].

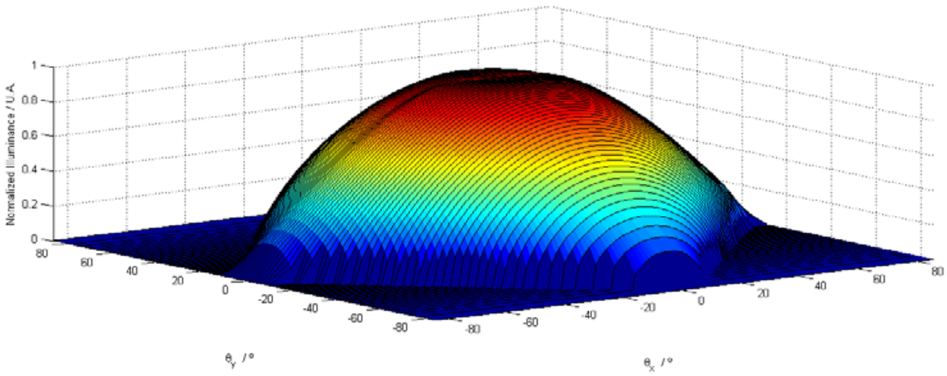
Graphs on Illuminance distributions



a) High brightness blue 40°



b) High brightness White 60°

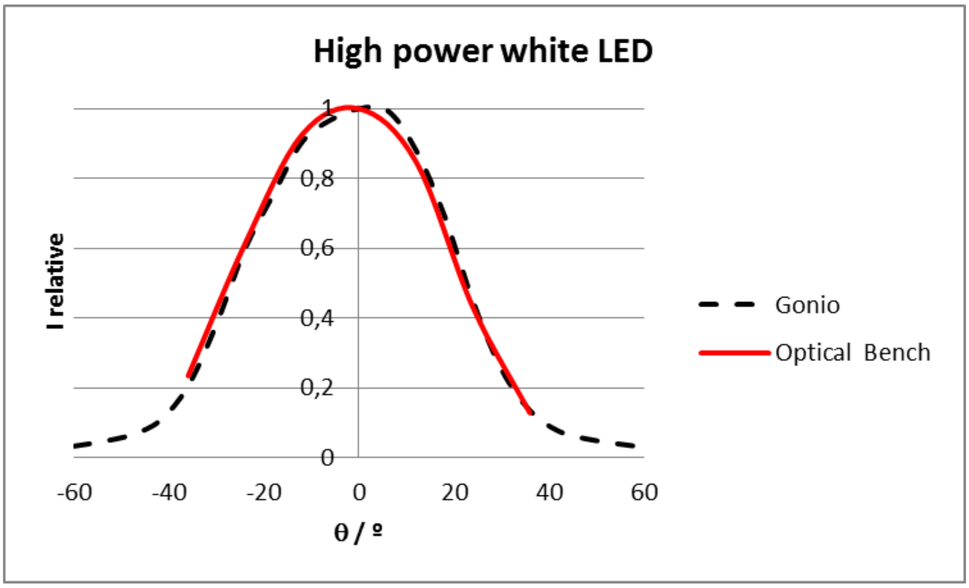


c) High power white 90°

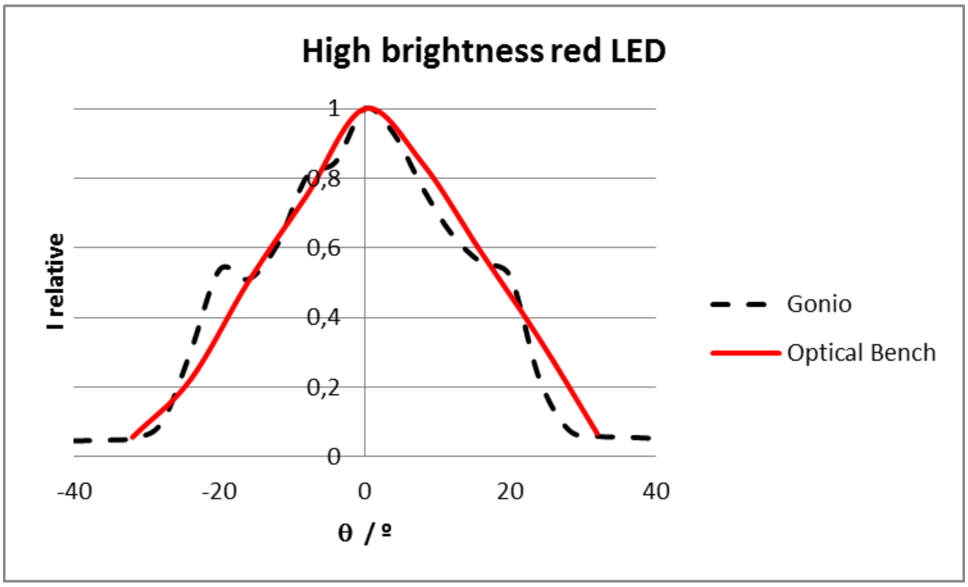
Figure 3. Angular distribution illuminance of LEDs as measured from the GEFE setup. a) high brightness blue LED nominal divergence 40 °, b) high brightness white LED nominal divergence 60 °, c) high-power white LED nominal divergence 90°

Some asymmetries that could be attributed to defects in encapsulation of the LEDs were observed.

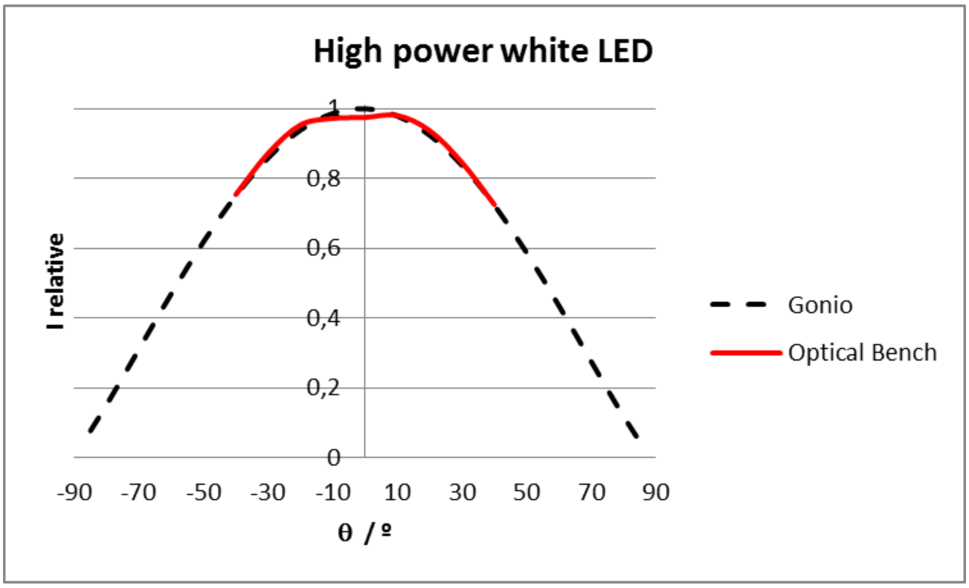
Comparison between both systems



a)



b)



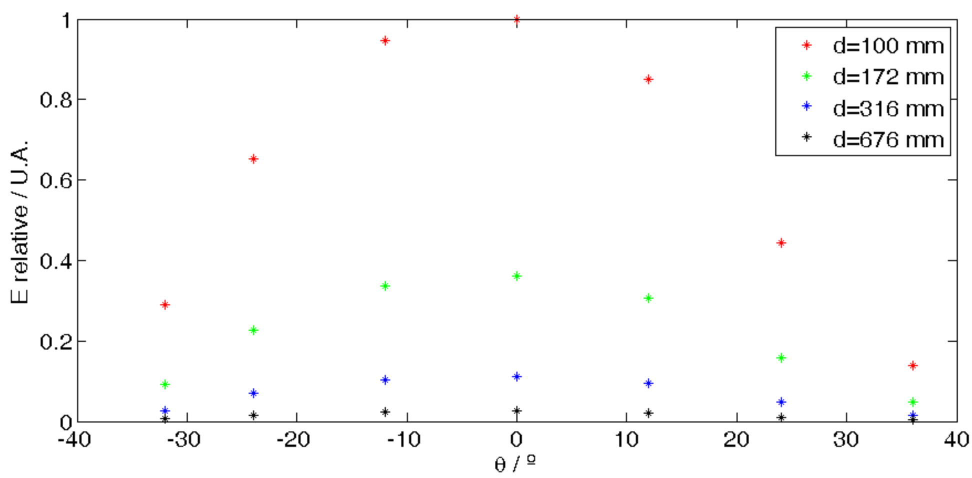
c)

Figure 4. Comparison of the illuminance distribution obtained from GEFE and optical bench measurements along the horizontal angle (θ, ϕ = 0).

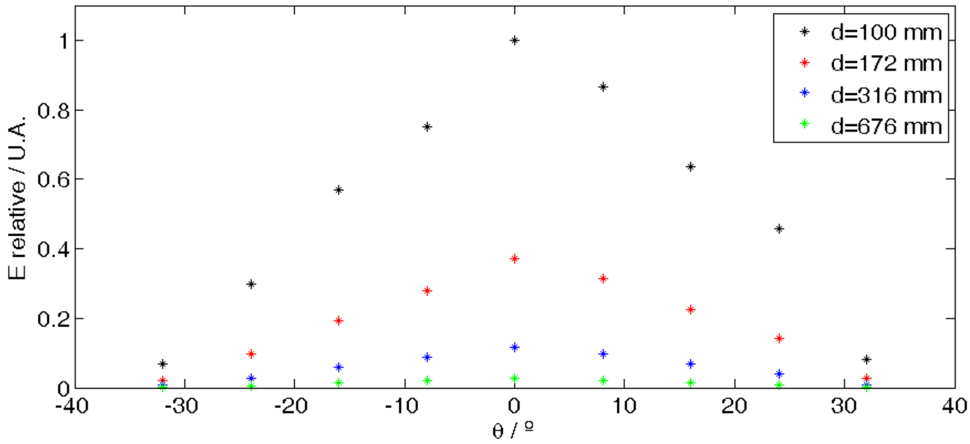
By fitting the values of the measured intensity distributions to a Lambertian function $I(\theta) = I_0 cos^n(\theta)$, values of n = 8.00; n = 13.63 and n = 1.14 were obtained for the LEDs a), b) and c) respectively.

Angular distributions as a function of distance

The measured angular distribution curves of a high-power white LED and a high brightness red LED at four distances are presented in figure 5 (a) and (b).



a)



b)

Figure 5. Angular distribution of LEDs at four distances along the horizontal angle (θ, ϕ = 0).

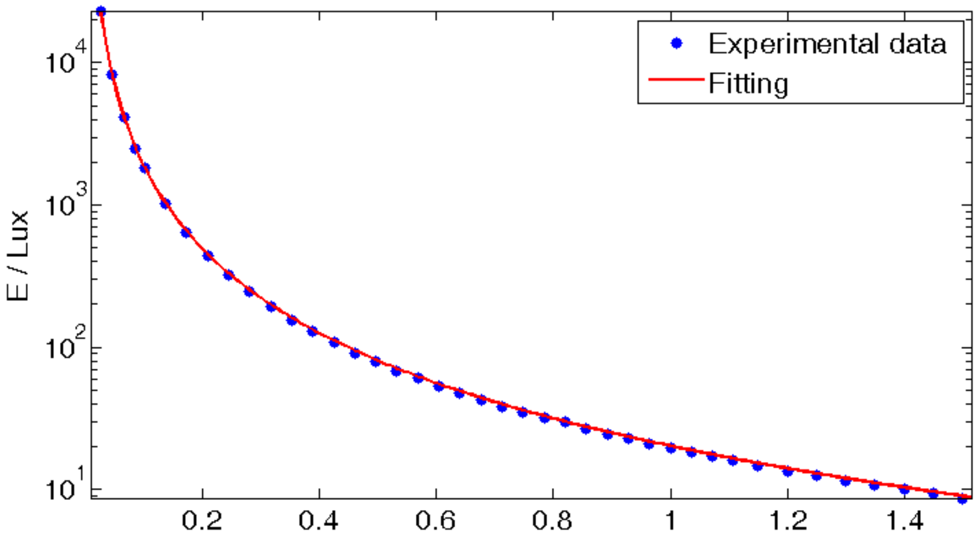
Illuminance as a function of distance ($\theta = 0$, $\phi = 0$)

The measured illuminance as a function of distance of high power LEDs (white, red and green) and high brightness LEDs (white, red and blue) are presented in figure 6 (a), (b), (c), (d), (e), (f). As it can be seen all the selected LEDs present a similar behavior. The obtained fitting is also shown. In a first approximation we have chosen a simple modified inverse-square law model, in the form:

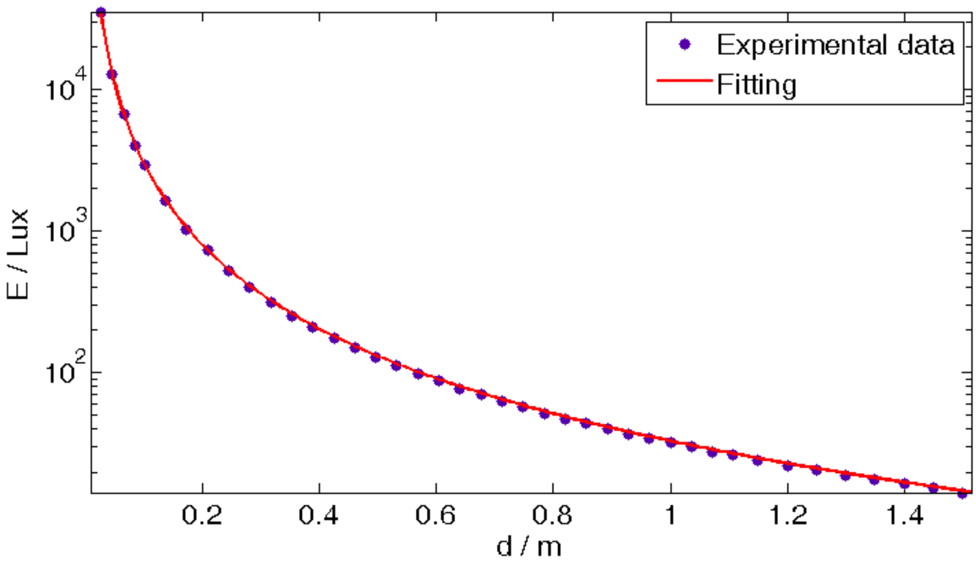
$$E_v(d) = \frac{I_v}{(d + \Delta d)^2}$$

with I_v as the luminous intensity of the LED, E_v as the illuminance measured, d the distance between the detector reference plane and the LED tip and the offset Δd representing the virtual source of the LED with respect to the front tip of the LED. Very good agreement ($R^2 \cong 1$) has been obtained for all the LEDs measured [4].

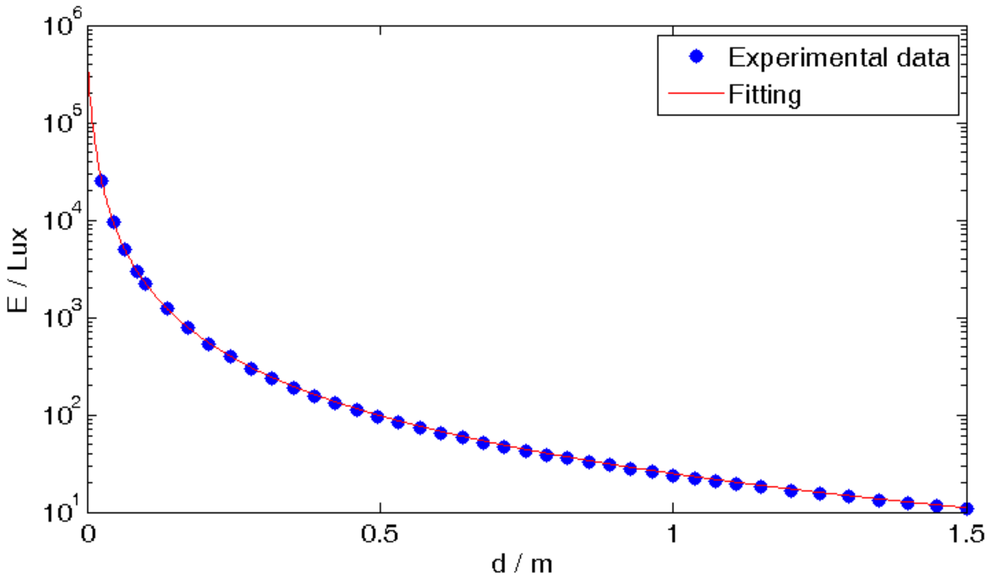
A modified model [5] that includes parameters as effective radii of virtual source and photometer aperture has been also tested. Negligible improvement was obtained.



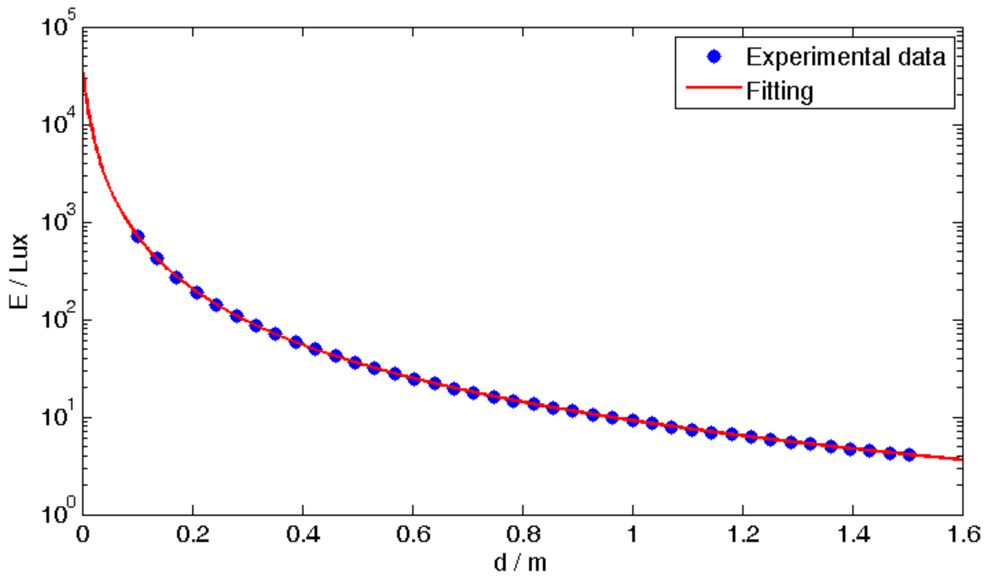
a) High Power LED white.



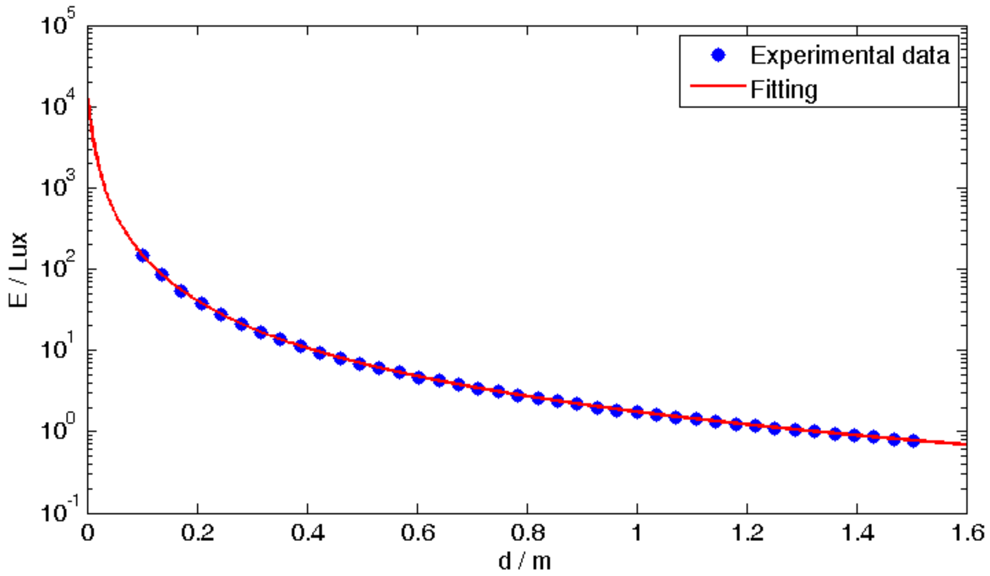
b) High-power LED red



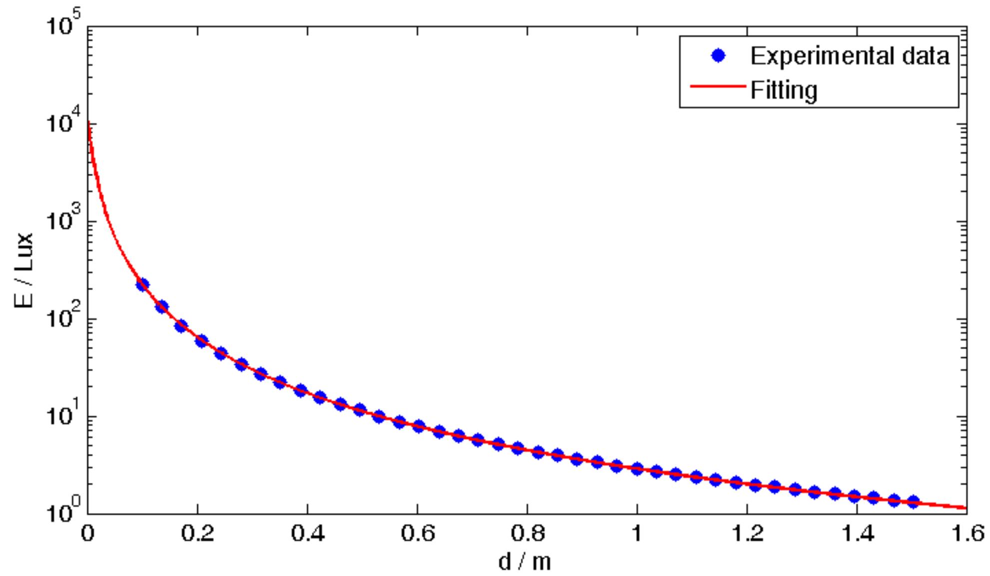
c) High-power LED green



d) High brightness white LED



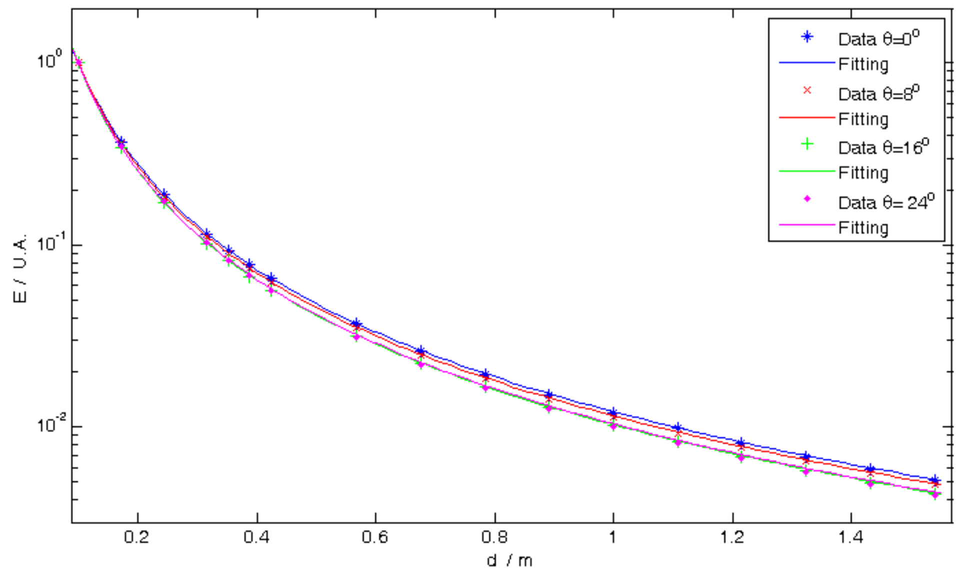
e) High brightness red LED



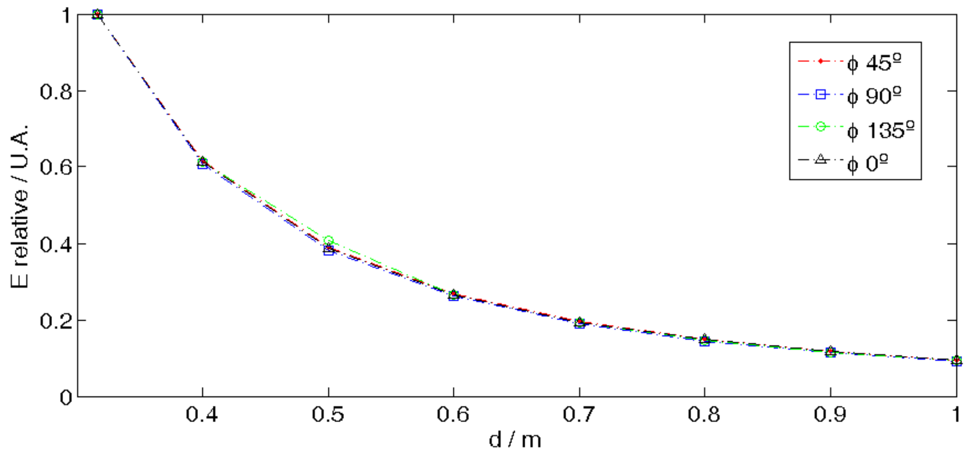
f) High brightness blue LED

Figure 6. Illuminance as a function of distance for different LEDs (θ =0, ϕ =0)

Illuminance as a function of distance for different horizontal angle (θ, ϕ =0)



Illuminance as a function of distance: dependence on ϕ, θ = 16°



Conclusions

Angular and spectral distribution as well as illuminance dependence with distance were measured using different high brightness and high power LEDs. A simple modified inverse-square law of the distance dependence model was proven to be useful for all the LEDs.

Angular distribution as a function of distance was also measured. Preliminary measurements indicate that the offset Δd can be modeled to some extent using a function of the form:

$\Delta d(\theta) = \Delta d_0 cos^p(\theta - \theta_0)$ with p related to divergence angle.

References

[1] Rabal A M *et al* 2012 Automatic Goino-spectrophotometer for the Low-uncertainty Absolute Measurement of the Out-of-plane Bidirectional Reflectance Distribution Function *Metrologia* **49** 213-223.

[2] CIE Technical Report, ``Measurements of LEDs'', CIE **127**, (2007).

[3] Villamarin A *et al* 2012 Angular and spectral radiant intensity distribution of high brightness white LEDs *Optic. Pura Aplic.* **45** 131-136.

[4] Villamarin A *et al* 2012 Study of Illuminance as a function of distance for high-brightness LEDs *Proceedings X National Conference on Optics.*

[5] Manninen P *et al* 2007 Method for analyzing luminous intensity of light-emitting-diodes *Meas. Sci. Technol.* **18** 223-229