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IMAGING METHOD FOR LUMINOUS FLUX MEASUREMENT

BY

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Abstract. Luminous flux measurement for luminaires is a traditional laboratory method. A fast method is presented for measuring luminous flux, without the need for an integrating sphere or photo goniometer. The principle is based on measuring the luminance of a screen, on which the flux is incident. To measure the entire emitted flux, the luminaire is virtually framed in surfaces on which luminance is measured, surfaces that close a complete volume of a parallelepiped. Because the luminaire has a symmetrical luminous flux distribution, only three measurements are required in this case. Details of the laboratory setup are presented, as well as the importance of the screen surface, which must be perfectly diffusive. The reflections that deviate from Lambert's law is highlighted by the variation of the luminance in transversal and longitudinal directions, relative to the screen. These transversal and longitudinal profiles serve also to validate the measurements.

Keywords: Lambertian reflection, luminance measurement, digital camera.

1. Introduction

The evolution of measurements in lighting is a very interesting one, which is the subject of topical monographic research (Bertenshaw, 2020). From this perspective, it can be said that this evolution is not over. There are concerns

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in the direction of traceability between flux and illumination standards, in order to simplify methods based on the integrating sphere. In this sense, (Fiorentin and Scroccaro, 2008) seeks other methods to measure the luminous flux, based on the link between the emitted flux and illumination, but using a goniometric method, to obtain the data necessary to calculate an integral on a spherical surface. The same research direction is continued by (Terrich, 2016), which aims to measure a light flux standard. The method is also based on a goniometer with which the light intensity is measured according to Eq. (8) from (Terrich, 2016). However, the same authors propose a controversial statement: "For symmetrically emitting light source is sufficient to measure luminance line only in primary-C planes (C0, C90, C180, C270) with a step $\Delta\Theta$ = 2°". In the author's opinion, it is obvious that it cannot be about the luminance of the source, but about the indirect measurement of the light intensity, by means of the normal illumination at a known distance, imposed by the construction of the photogoniometer.

Methods based on the integrating sphere and the photogoniometer are useful in the laboratory, but are not applicable in the field. For measuring the luminous flux for complex scenes, in the presence of artificial and natural lighting, HDR-based imaging methods are increasingly used (Poling and Cai, 2020). Basically, each pixel measures the incident light intensity, which is then integrated into a hemisphere. Luminous flux measurement is the concern in (Mardajlevic *et al.*, 2009), with particularization for the incident flux through windows, through light tubes or the incident flux from the clear or overcast sky. A relationship between illumination and flux is sought, but it operates with the illuminance incident on the front-side plane of the paper, generated by the flux to be measured. An HDR-based imaging method (High Dynamic Range) is then used to measure the luminance field. The use of a screen to measure the luminous flux was also the basis of the method in this paper, especially since the method uses the diffuse screen in a classic way and not through transparency. The method is continued by (Moeck and Anaokar, 2006) and is applied to the study of historical monuments (Dome of the State Capitol in Pennsylvania). An interesting information is obtained regarding the weights of each surface that contributes to the formation of the visual sensation. In the author's opinion, these results do not have a very exact utility, unlike the measurement of the luminous flux emitted by a luminaire, which is the objective of this work.

Measuring the luminance of various surfaces, geometrically delimited, is also of interest for tunnel lighting (Doulos *et al*., 2020), where energy optimization is very important. It is demonstrated that the luminances of the surfaces included in the angle of 20 degrees (L20) at the entrance to the tunnel can be measured. But the precise optics of the cameras allow even more, by coupling the luminance measurements with the complete geometric information, respectively photogrammetry (Cai, 2013). In this way, synchronous luminance measurements can be approached, for dynamic scenes, where the location of light sources in space is also important. For the present paper, the measuring scene being static, the delimitation of the surfaces could be achieved by using simple black markers for the white background. In the case of measuring the flux emitted by luminaires through luminances (Jakubiec *et al*., 2016) states that there are certain limitations for HDR.

In order to avoid the problems of measuring extreme luminances (the case of LEDs or incandescent lamps) in this work the luminance of a surface illuminated by the luminaire is measured. For the situation in which it is important to measure all the luminances in the visual field but also continuously (daytime, evening or night scenes) then there is the possibility to use embedded microsystems, much more accessible compared to a digital camera (Mead and Mosalam, 2016).

There are other works, just as recent, that address the measurement of the luminous flux of luminaires. One such example is (Huriev and Neyezhmakov, 2018) who are concerned with the metrological traceability of measurements of the luminous flux standard based on LED lamps. This paper reports the problem of the various spectral composition of LEDs, which causes measurement errors. To reduce these errors, the camera used by the author in current research was subjected to an internal self-calibration process on a white surface exposed to the measured source, to weight the RGB response, to comply with the condition specified by Eq. (8) in (Kruisselbrink *et al*., 2019).

2. The Measurement Method

The imaging method is based on the definition relationship of illumination, as an expression of the reception of the luminous flux $d\emptyset$ by the small surface dS:

$$E = \frac{d\emptyset}{dS} \tag{1}$$

The illuminated surface, if it is perfectly diffusing and with a reflectance ρ thus it will have a value for luminance:

$$L = \frac{\rho}{\pi} E \tag{2}$$

Obviously, as the luminous flux is not uniform, neither the illumination nor then the luminance will be constant on the work surface. The total luminous flux incident on the work surface is obtained by integrating Eq. (1) on the entire area considered:

$$\emptyset = \int_S L(s) \frac{\pi}{\rho} dS \tag{3}$$

This integral will have to be solved using the luminance values extracted from the digital image.

The total luminous flux emitted by a luminaire can then be calculated if we make sure that the entire luminous flux is incident on corresponding computing surfaces, which enclose a complete parallelepiped. For effective measurements, an important condition is also necessary, namely to eliminate the possibility of reflections between interior surfaces. This generates an internal contradiction of the method, because in order to have a luminance distribution according to Eq. (3) it is necessary to work with relative high reflection coefficient, but which also generate multiple reflections, with the role of amplifying the total flux. In order to keep the equality between the flux emitted by the lamp and the one received by the work surfaces, the measurements were performed successively, on a single work surface. The measurements were performed in a large darkroom, so that the reflected flux is negligible. To verify the principle of the method, the lighting configuration that was later used for measurements was simulated in DiaLUX EVO 9.1. In Fig. 1 is available the configuration of the experimental stand, simulated in DiaLUX:

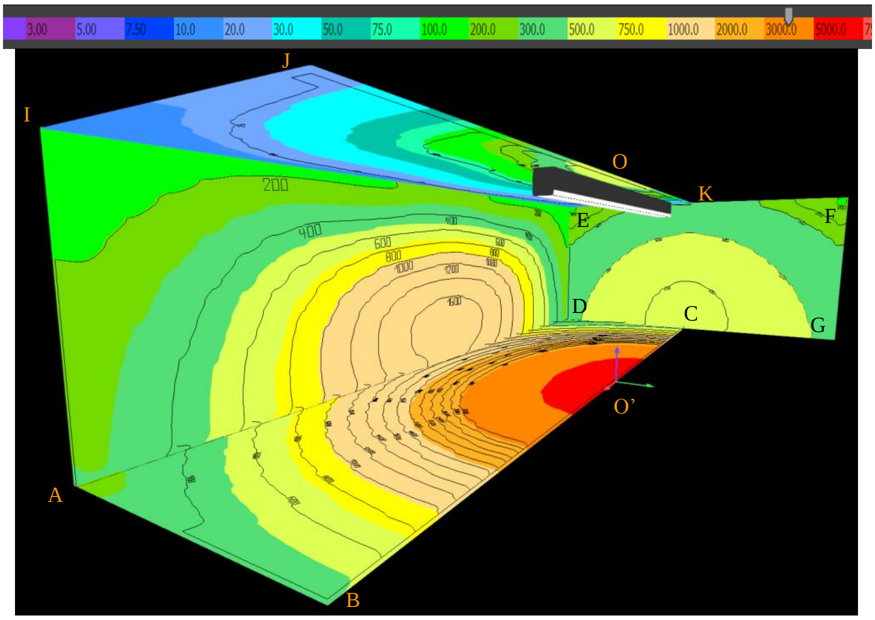

Fig. 1 – The luminaire position relative to virtual calculation surfaces, and illumination level (lx).

The main calculation surfaces are as follows:

a) ABCD – horizontal surface, dimensions 2.37 x 0.585 m

b) DEFG – vertical ending surface, 1.17 x 0.585 m

c) AIED- lateral horizontal surface, 2.37 x 0.585 m
d) IJKE – lower illuminated horizontal surface, 2.37 x 0.585 m, required for simulation in DIALUX, where the body used did not have a completely lower emission. This surface was no longer required for measurements.

For the measurements, a single work plane was used, fixed and with a lower location. In order to measure the luminance on a vertical plane, the position of the luminaire was changed, as exemplified in Fig. 2:

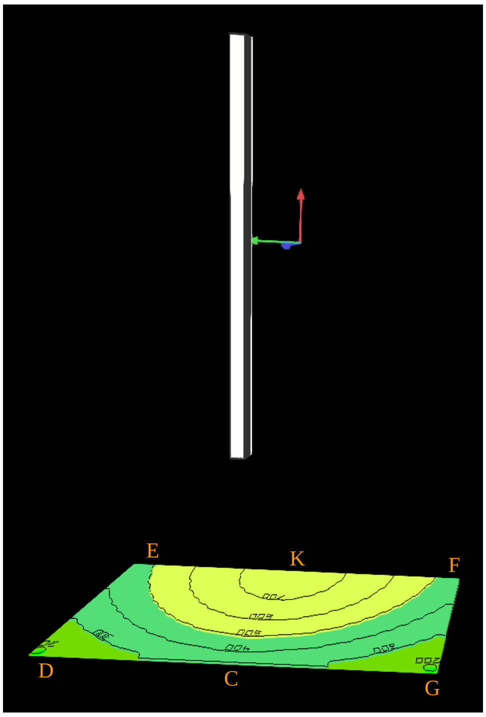

Fig. 2 – The luminaire position in the field for luminance measurement on virtual vertical calculation surface DEFG.

To validate the calculation method, the results calculated for the test problem in Fig. 1 are presented in Table 1, which will then be the basis of the imaging measurements. In Table 1 the values of the incident flux are multiplied by 2, to take into account the symmetries in the horizontal plane or the fact that the model implies the existence of two vertical surfaces that completely frame the parallelogram. The type of distribution used is not important, and the luminous flux installed in the lamp is 8900 lm, so that the coincidence of the results is perfect, being affected only by some rounding of the numbers.

Table 1
The Luminous Flux Received by the Calculation Surfaces from Fig. 1

Surface (Fig. 1)	Illumination average	Dimension	Dimension	Area	Incident flux	Total
	(lx)	(m)	(m)	(m^2)	(lum)	(lum)
ABCD	2143	2.37	0.585	1.386	2971	5942
DEFG	499	1.17	0.585	0.684	342	683
ADEI	722	2.37	0.585	1.386	1001	2002
IJKE	98.1	2.37	0.585	1.386	136	272
						Total: 8899.5

3. The Imaging Measurements for Luminance

The experimental measurements followed the geometry in Fig. 1, and started with the horizontal surface ABCD, for which an image from 4 m height was taken, in order to reduce the distortions. The luminance field is available in Fig. 3:

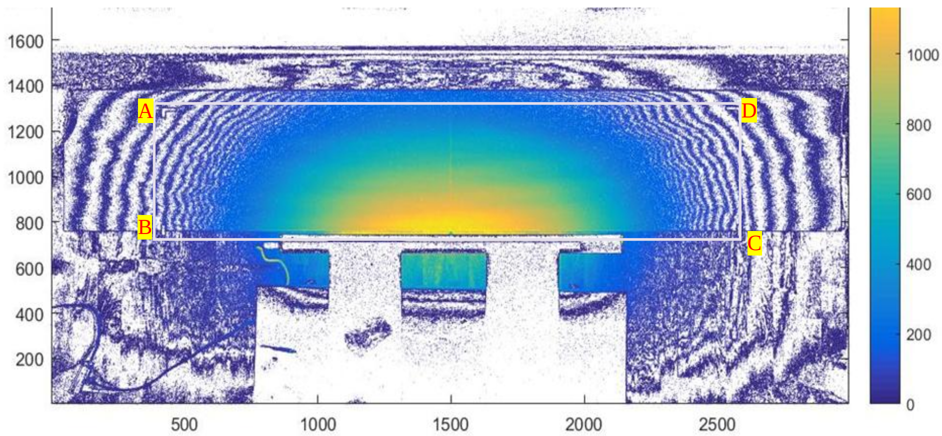

Fig. 3 – The luminance field for horizontal surface ABCD, (cd/m^2).

The inner surface is framed in the yellow rectangle, with the actual physical landmarks visible on the inside, at the corners. The calculated average luminance is 414.12 cd/m^2.

The next surface for which the luminance was measured is ADEI, from Fig. 1. To perform this imaging measurement, the luminaire was rotated around the longitudinal axis by 90°. Luminance distribution is available in Fig. 4:

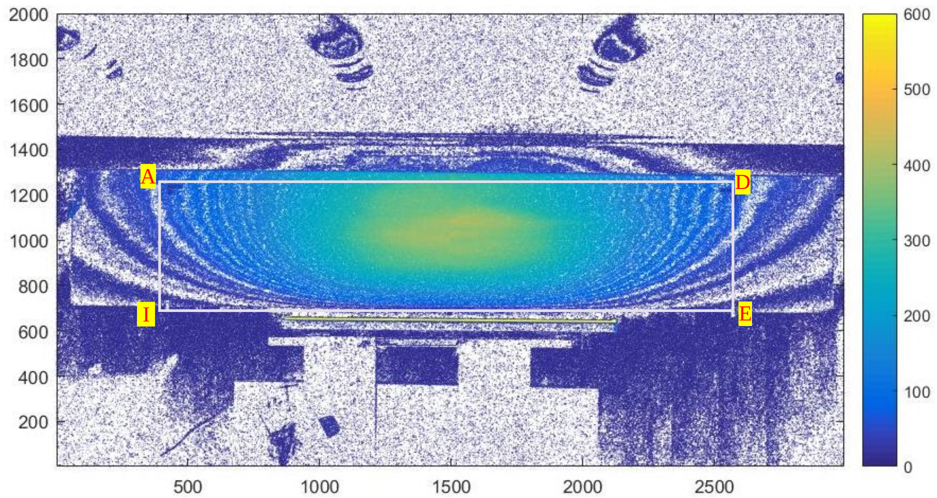

Fig. 4 – The luminance field for vertical surface ADEI, (cd/m^2).

The average luminance was: 178.15 cd/m^2

In similar way it was measured the luminances for vertical surface DEFG:

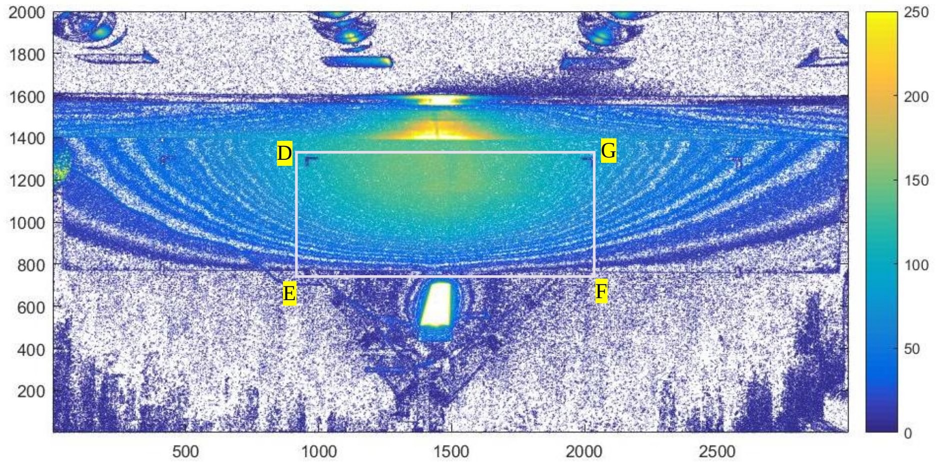

Fig. 5 – The luminance field for vertical surface DEFG, (cd/m^2).

The average luminance for the DEFG area was 79.53 cd/m^2.

With these luminance values it is possible to proceed to the calculation of the incident / emitted flux, in Table 2:

Table 2
The Luminous Flux Calculated from Imaging Measurement of Luminance from Fig. 3-5

Surface	Area	Mean Luminance	Reflection coefficient	Mean Illumination	Luminous Flux
-	m^2	cd/m^2	-	lx	lm
ABCD	1.38	414.12	0.62	2098.3	2909.3
ADEI	1.38	178.15	0.62	902.7	1251.5
DEFG	0.67	79.53	0.62	402.9	271.1
DEFG	0.67	79.53	0.62	402.9	271.1
ADEI	1.38	178.15	0.62	902.7	1251.5
ABCD	1.38	414.12	0.62	2098.3	2909.3

The total luminous flux will be 8863.8 lm (the sum of the right column), confirmed based a measurement performed at SC GreenTEK SRL, using integrating sphere method. The differences are below 5%, and this is acceptable for a fast method. The error sources are multiple, including geometry and position of the luminaires and working surfaces. The most important source of errors comes from the main hypothesis of the method, namely that the surface on which the light is incident is perfectly diffusing, a necessary condition for Eq. (2) to be valid. A supplementary assessment was necessary in this direction.

4. The Surface Reflection Properties

The material used for the screen was from the beginning chosen for diffuse reflective properties. A matte cardboard with a rough surface was used. Even the angular reflective coefficients were measured, an aspect highlighted in other works, such as the experimental stand in Fig. 7 from (Gălăţanu, 2017).

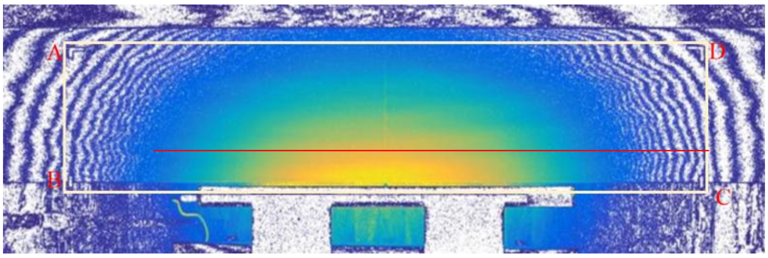

Fig. 6 – The longitudinal luminance profile (red) for horizontal surface ABCD, (cd/m^2).

In order to study the reflection mode of the material, to be able to compare various materials, the luminance values were extracted along the screen, the red line from Fig. 6, located at various distances from the vertical plane containing the luminaire (from 100 to 100 mm).

One material that seemed very suitable for use as a screen was expanded polystyrene. The high roughness and random granulation were to the advantage of diffuse reflection. After the first measurements, very high values for luminance were observed, much higher compared to other materials with a similar degree of white. The longitudinal profile of the luminance revealed qualitative and quantitative aspects that contradicted the diffuse type reflection, as seen in Fig. 7:

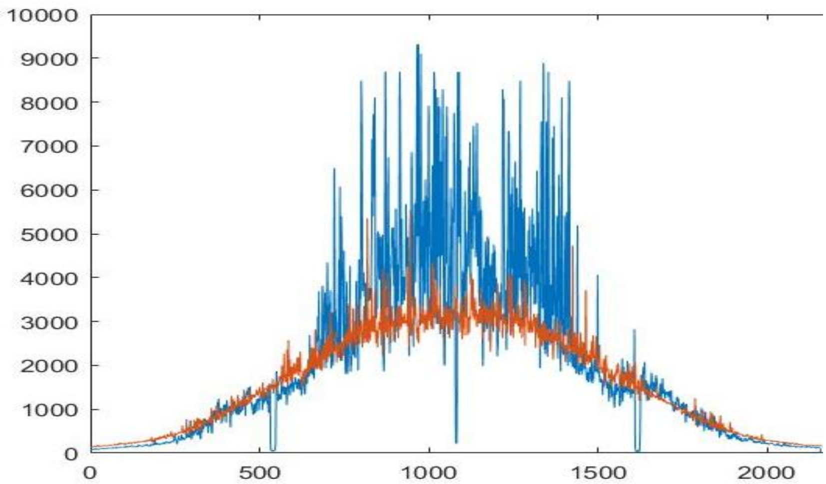

Fig. 7 – The longitudinal luminance profile (Blue – 0 mm, Orange – 100 mm) for horizontal surface ABCD, (cd/m^2).

With blue there are very high values of luminance, just below the luminaire and in the direction of the digital camera. Here is present not only a guided reflection, but even a catadioptric effect.

Another material that raised a question mark was a certain cardboard, with a matte appearance. At the detailed analysis, for which several longitudinal profiles of the luminance distribution were made, a similar effect was highlighted, according to Fig. 8. For this cardboard, five profiles of the luminance were visualized, starting with the normal plane and continuing with an increase of the distance of 100 mm. It was observed that the luminance of the area corresponding to the normal reflection is lower than the luminance of the area at 100 mm, which indicates a different kind of reflection, respectively specular reflection. Since the reflection is not of the Lambert type, this material has not been used for the screen either. In the end, a textile material was used, with a full texture and fleece effect, which practically covered the inherent pattern of the fabric.

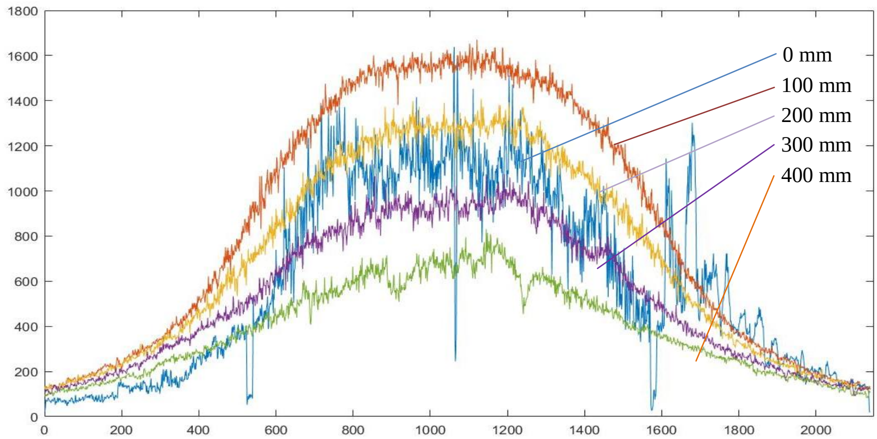

Fig. 8 – The longitudinal luminance profiles for horizontal surface ABCD, (cd/m^2), specular reflections.

5. Conclusions

Luminous flux measurement for a luminaire is an operation that requires specialized equipment, based on a large integrating sphere or a large darkroom, for the photogoniometer. The proposed method requires a relatively small darkroom, because the imaging method can be applied from a short distance. The accuracy of the measurements is influenced by the reflective properties of the screen material, and therefore this parameter must be carefully analyzed. For the presented case, the situations when the screen material produced scattered reflections was also highlighted by imaging methods.

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METODA IMAGISTICĂ PENTRU MĂSURAREA FLUXULUI LUMINOS

(Rezumat)

Măsurarea fluxului luminos pentru corpuri de iluminat este o metodă de laborator tradițională. Lucrarea prezintă o metodă rapidă de măsurare a fluxului luminos, fără a fi necesară sfera integrativă sau fotogoniometrul. Metoda este imagistică și extinde numeroasele aplicații care se cunosc astăzi pentru măsurarea luminanței. Principiul se bazează pe măsurarea luminanței unui ecran pe care fluxul este incident. Pentru a măsura întreg fluxul emis, corpul de iluminat este încadrat virtual în suprafețe pe care se măsoară luminanța, suprafețe care închid un volum complet al unui paralelipiped. Deoarece se utilizează proprietățile distribuției simetrice pentru fluxul

luminos, în cazul prezentat sunt necesare numai trei măsurători. Se prezintă detalii ale setup-lui de laborator, precum și importanța suprafeței ecranului, care trebuie să fie perfect difuzivă. Apariția reflexiilor care se îndepărtează de legea lui Lambert este pusă în evidență prin modul de variație al luminanței transversale. Aceste profiluri transversale sau longitudinale servesc și la validarea măsurătorilor.