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EVALUATION OF THE PERFORMANCE OF A ROAD SURFACE GONIOREFLECTOMETER

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Abstract

The reflection properties of the road pavement depend on the material and the texture of its surface. They can be specified with a set of luminance coefficients, which can be measured thanks to a gonioreflectometer. We presented in a previous paper a gonioreflectometer designed for in-lab measurements, especially suited for public lighting applications. We present in this paper a metrological evaluation of this instrument. First, we compare measurements from the gonioreflectometer with measurements taken with an illuminancemeter and a luminancemeter. Then we look at measurements in two analytically tractable cases. Finally, we perform uncertainty calculations on the luminance coefficients, and extend the results to the road lighting application by calculating uncertainties on the lightness and specularity parameters. We also evaluate the influence of uncertainties on the performance of a given lighting design for two types of road surfaces. Our results indicate that the achieved uncertainties have a limited influence.

Keywords: BRDF, Metrology, Uncertainty, Photometry, Lighting, Gonioreflectometer, Goniophotometer, Luminance coefficient, Road surface

1 Introduction

The reflection properties of the road pavement must be taken into account when designing road lighting installations (CIE, 1984). These properties depend on the material and the texture of the road surface and can be specified by means of a set of luminance coefficients. The luminance coefficient q is defined as the ratio between the luminance L of a point on a surface, and the horizontal illuminance E produced at the same point by a lighting installation. This coefficient varies both with the lighting and viewing directions, and is thus also referred to as the Bidirectional Reflectance Distribution Function (BRDF). In other words, this coefficient depends on four angles (Figure 1), namely:

- α, viewing angle;
- β, angle between the lighting plane and the viewing plane;
- γ, lighting angle;
- δ, angle between the viewing plane and the road axis at the considered viewing point P.

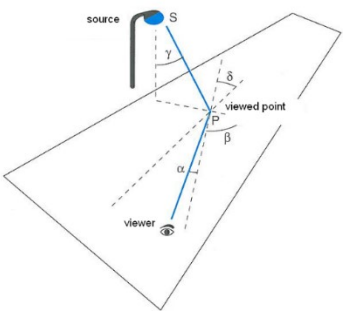

Figure 1 – Definition of the angles for luminance coefficient measurements

Road surfaces being nearly isotropic, the influence of δ is usually neglected.

The luminance coefficient may be determined by means of a gonioreflectometer. Ifsttar's instrument was designed for in-lab measurements. It was extensively presented in a previous paper (SAINT-JACQUES, 2017). The present paper briefly recalls the operation of the instrument in Section 2, and subsequently focuses on the evaluation of its performance. We start in Section 3 with direct measurements in simple geometries and with computations in analytically tractable cases (with a quasi-lambertian surface and a quasi-specular surface). In Section 4, we compute the uncertainty on the luminance coefficient, and then we extend the results to the parameters Q_0 and S_1 which are used to describe road surface properties for road lighting applications. Section 5 then investigates the influence of the uncertainty of the measurements in the computed performance of a lighting installation. Section 6 presents conclusions on the metrological qualification of our instrument and proposes future work.

2 The gonioreflectometer of IFSTTAR

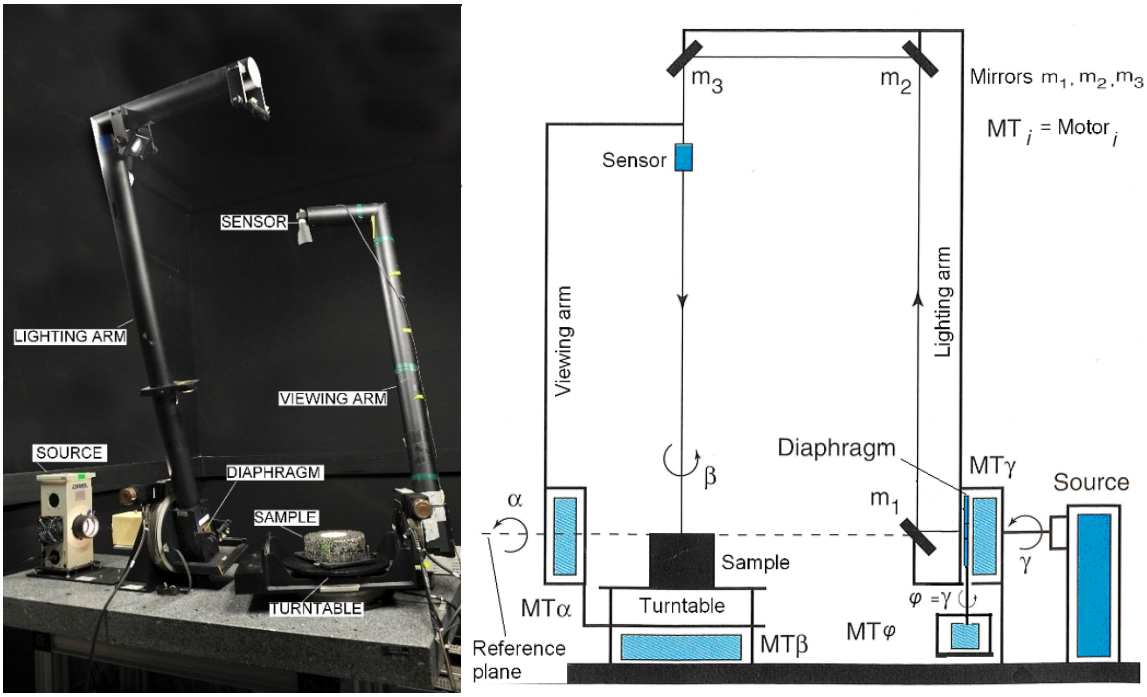

Figure 2 – The gonioreflectometer of IFSTTAR : Picture (L) and Operation diagram (R)

The operation of the gonioreflectometer is summarized as follows. The incoming light beam from a 250-W still halogen lamp is projected onto the surface sample thanks to a system of mirrors along a 150-cm rotating arm (the lighting arm). The surface sample is set on a rotating turntable which is fixed to another 150-cm rotating arm (the viewing arm), at the end of which is attached a photoelectric sensor. The sensor comprises a photopic luminous efficiency function ($V(\lambda)$) filter and measures the illuminance which results from the reflection on the lit surface sample.

The measurement protocol is detailed in a previous paper (SAINT-JACQUES, 2017). It necessitates a prior calibration phase where illuminance measurements are performed with a quasi-lambertian surface (Spectralon® from Labsphere) whose reflectance ρ is known by calibration.

3 Validation of measurements

An obvious way to validate measurements obtained by means of our gonioreflectometer is to compare our measurements with some references. To the best of our knowledge, there are not yet, any such reference measurements or reference materials for BRDF measurements. We thus propose to validate our measurements by combining two methods: comparisons with direct

measurements in a few geometries, and comparisons with calculations for analytically tractable cases, namely a lambertian surface and a specular surface.

3.1 Direct measurements

A straightforward way to measure the luminance coefficient is direct measurement with an illuminancemeter and a luminancemeter, although this approach is practically feasible for a limited number of geometries.

We chose to implement this approach with a diffuse surface (Spectralon) in three geometries in a specular reflection (β=0°): (α=5°; γ=0°), (α=10°; γ=0°) and (α=10°; γ=10°).

We used a calibrated luminancemeter to measure the luminance L reflected by the surface. For the illuminance E produced by the gonioreflectometer on the surface, we averaged measurements taken with a calibrated illuminancemeter in 5 different locations on the surface. We then proceeded to compute $q = L / E$.

The results are shown on the Table 1 below:

Table 1 – Luminance coefficient: direct measurements vs gonioreflectometer measurements

Geometries	α=5° β=0° γ=0°	α=10° β=0° γ=0°	α=10° β=0° γ=10°
Measured luminance L	680,6 cd.m^{-2}	757,4 cd.m^{-2}	738,3 cd.m^{-2}
Measured illuminance E	2824 lx	2824 lx	2029 lx
q=L/E (direct measurement)	0,2410 cd.m^{-2}.lx^{-1}	0,2682 cd.m^{-2}.lx^{-1}	0,3638 cd.m^{-2}.lx^{-1}
Output (q) from our gonioreflectometer	0,2287 cd.m^{-2}.lx^{-1}	0,2613 cd.m^{-2}.lx^{-1}	0,3869 cd.m-2.lx^{-1}
Relative deviation	5,1%	2,6%	5,9%

We obtain a relative deviation of 5,1 % for the viewing angle of 5°, and 2,6 % for the viewing angle of 10° for a normal illumination. For a given viewing angle of 10°, the relative deviation is two times higher (5.9%) at an illumination of 10° than at normal illumination. Nevertheless, as we will see from the uncertainty analysis in section 4, these results are satisfactory.

3.2 Analytic cases

Another simple means to validate the measurements from our gonioreflectometer (at least for some lighting/viewing geometries) is to consider surfaces whose reflection properties can be described analytically. We implement this approach with a quasi-lambertian surface and a quasi-specular surface.

3.2.1 Lambertian surface

We consider a diffuse surface whose calibrated reflectance ρ is known for a certain geometry: a normal lighting direction and a viewing angle of 45°. Then its theoretical luminance coefficient is constant and equals ρ / π. It can be compared with the luminance coefficient measured with our gonioreflectometer for the same lighting and viewing angles. Figure 3 presents the measured values for various values of β between 0° and 180°, as well as the mean of measured values, and the theoretical value. The mean value of the measured luminance coefficient is 0,3281 cd.m^{-2}.lx^{-1}, and the standard deviation is 0,0003 cd.m^{-2}.lx^{-1} (i.e. less than 0,1 %), so the relative deviation from the theoretical value of 0,3231 cd.m^{-2}.lx^{-1} is 1,5 %, which is acceptable, considering the uncertainty on q evaluated in Section 4.

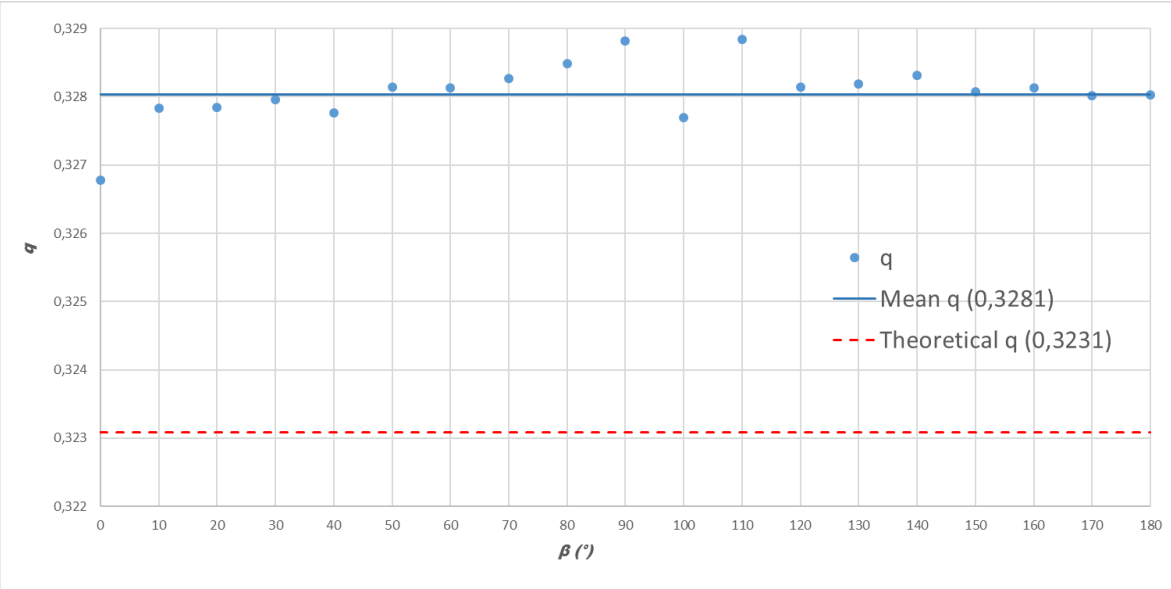

Figure 3 – Luminance coefficients measured for a calibrated diffuse surface

3.2.2 Specular surface

We consider the particular behaviour of a mirror to compute its luminance coefficient and compare it to the measured value. Indeed, a mirror is the most suited example of a quasi-specular material wherein incident light is reflected in the direction symmetrical to the lighting direction with respect to the normal of the mirror (Descartes law).

In the case of the mirror, all the incident luminous flux from the source is reflected in the same solid angle to the observer. The specular reflectance ρ, defined as the ratio between the reflected flux and the incident flux, can be expressed in the case of the mirror as the ratio of the reflected intensity I_r and the incident intensity from the source I_i.

$$\rho = \frac{I_r}{I_i} \tag{1}$$

The luminance L of the surface, as observed from an angle θ (i.e. $\pi/2 - \alpha$) from the normal to the surface, can be determined by measuring the luminous intensity I_r reflected by this surface whose lighted area (measured area) is S:

$$L = \frac{I_r}{S\cos(\theta)} \tag{2}$$

The illuminance E on the surface is:

$$E = \frac{I_i \cos(\theta)}{d^2} \tag{3}$$

where d is the distance between the source and the sample

From the previous equations, an expression of q is:

$$q = \frac{\rho d^2}{S\cos^2(\theta)} \tag{4}$$

where

q is the luminance coefficient,

d is the distance between the source and the sample (1,5m)

ρ is the specular reflectance of the mirror;

S is the lighted and measured area on the mirror (a 9,8 cm-diameter disk)

θ is the incident angle (to the normal to the surface, which is equally the viewed angle).

Figure 4 represents, for different incident angles, the expected theoretical value of *q* assuming a value of 0,98 for the reflectance of the mirror, and the measured values of *q* integrated over a 5°-cone around the specular direction. Indeed, the reflected beam is theoretically a Dirac function at the specular direction and no signal is found outside this direction, but in reality, some light is reflected around the specular direction.

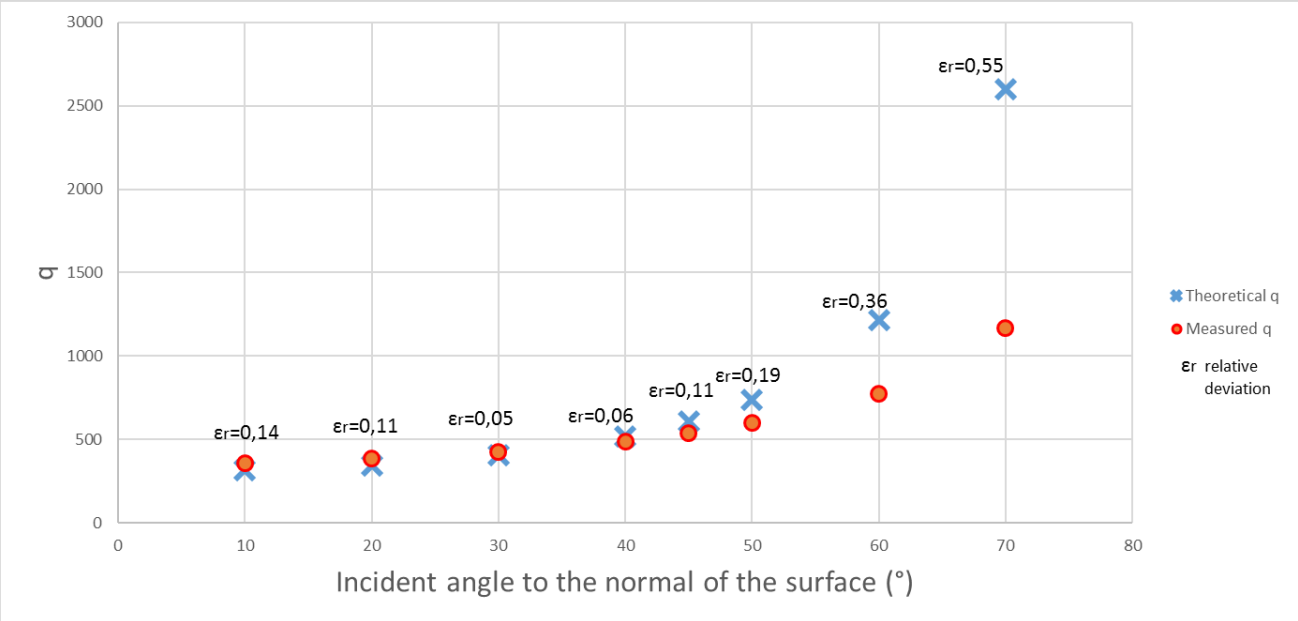

Figure 4 – Luminance coefficients of a mirror

It can be noted that the relative deviation of the measured values from the expected values ranges from 14 % at 10° incidence to 55 % at grazing angles, with deviations under 11 % between 20° and 45°. Important deviations at higher angles can be explained by the variations of the specular reflectance which depends both on the incident angle (the higher the angle, the lower the reflectance) and the spectrum (SCOARNEC, 2014), while we assumed a constant reflectance *ρ* of 0,98 for our mirror. Deeper investigations need to be done on the specular reflectance; nevertheless, the results shown on Figure 4 constitute a first-hand validation of the measurements, at least, for incidence angles up to 45°.

4 Uncertainty calculations

As detailed in the previous paper (SAINT-JACQUES, 2017), the luminance coefficient value is deduced from illuminance values measured on our gonioreflectometer using the following expression:

$$q(\alpha,\beta,\gamma) = \frac{\rho}{\pi\sqrt{2}} \cdot \frac{1}{sin\alpha} \cdot \frac{E_r(\alpha,\beta,\gamma)}{E_d(\gamma)} \tag{5}$$

where

$\underline{q}$ is the luminance coefficient,

ρ is the reflectance of a Spectralon, known by calibration for a 0°/45° geometry;

α is the viewing angle;

E_r is the illuminance reflected from the sample and measured by the sensor;

E_d is the illuminance reflected from the Spectralon and measured by the sensor during a prior calibration phase.

We hereafter present the methodology to compute uncertainties and for illustrative purpose, we henceforth mention, whenever relevant, numerical values for two road surface samples which we measured. We selected an R2-type surface (which will be named R2) and an R4-type one (which will be named R4) (CIE, 1984). The samples are shown in Figure 5.

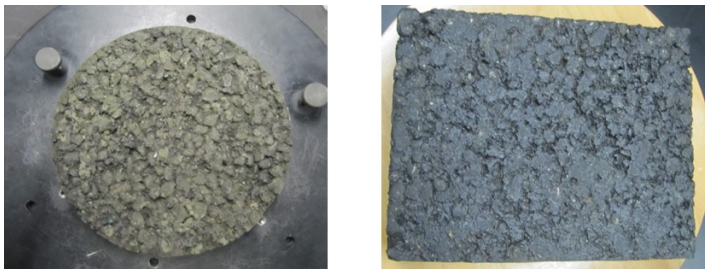

Figure 5 – R2 (L) and R4 (R) road surface samples

Two types of uncertainties will be evaluated (JCGM, 2008): type B and type A.

4.1 Uncertainty Type B

Type B uncertainty is evaluated by scientific judgement based on all of the available information on the possible variability uncertainties. In our case, as the expression of the luminance coefficient (Equation 5) depends on the viewing angle, the reflectance, and the illuminance values measured by the sensor during respectively the calibration and the measurement phases, the standard uncertainty of the luminance coefficient can be deduced from the combined standard uncertainties of these parameters.

Let *u(X)* be the standard uncertainty on the variable *X*. We can assume that uncertainties on the parameters intervening in the expression of the luminance coefficient in Equation 5 are statistically independent. Then the combined standard uncertainty on *q* noted *u(q)* is:

$$u(q)^2 = \left(\frac{\partial q}{\partial \alpha}\right)^2 u(\alpha)^2 + \left(\frac{\partial q}{\partial \rho}\right)^2 u(\rho)^2 + \left(\frac{\partial q}{\partial E_r}\right)^2 u(E_r)^2 + \left(\frac{\partial q}{\partial E_d}\right)^2 u(E_d)^2 \tag{6}$$

where

$$\frac{\partial q}{\partial \alpha} = -\frac{\rho}{\pi\sqrt{2}} \cdot \frac{cos\alpha}{(sin\alpha)^2} \cdot \frac{E_r(\alpha,\beta,\gamma)}{E_d(\gamma)} \tag{7}$$

$$\frac{\partial q}{\partial \rho} = \frac{1}{\pi\sqrt{2}sin\alpha} \cdot \frac{E_r(\alpha,\beta,\gamma)}{E_d(\gamma)} \tag{8}$$

$$\frac{\partial q}{\partial E_r} = \frac{\rho}{\pi\sqrt{2}sin\alpha} \cdot \frac{1}{E_d(\gamma)} \tag{9}$$

$$\frac{\partial q}{\partial E_d} = -\frac{\rho}{\pi\sqrt{2}sin\alpha} \cdot \frac{E_r(\alpha,\beta,\gamma)}{E_d(\gamma)^2} \tag{10}$$

We can note from Equations 6 and 7 that the more grazing the viewing angle, the higher the uncertainties.

We have to determine *u(X)* of the four influence parameters: ρ, α, E_r, and E_d. They are computed, either thanks to the material manufacturers' specifications, or by calibration.

Concerning the viewing angle, as we use a step by step motor to make the viewing arm rotate of an angle of α degrees, the uncertainty is the resolution uncertainty of the motion controller of the motor. For $= 1°$:

$$\frac{u(\alpha)}{\alpha} = 0{,}03\ \% \tag{11}$$

As regards the reflectance ρ, the Spectralon is regularly calibrated and the resultant uncertainty is:

$$\frac{u(\rho)}{\rho} = 4{,}9\ \% \tag{12}$$

Eventually, we have to determine uncertainties on $E_r(\alpha, \beta, \gamma)$ and $E_d(\gamma)$, which involve the same chain of measurement acquisition, whether for the calibration phase or for the measurement phase. That acquisition chain consists of a sensor (calibrated in illuminance), an amplifier/converter (which converts and amplifies an electric current into a voltage) and a voltmeter (which reads the converted value).

$$u(E_r) \text{ or } u(E_d) = \sqrt{u(_{amplifier})^2 + u(_{voltmeter})^2 + u(_{sensor})^2} \tag{13}$$

The assessment of the uncertainties arising on each of these instruments is done thanks to the manufacturer's specification. Even though the chain of measurement is the same for E_d and E_r , uncertainty values are quite different because E_d is measured on a flat surface (Spectralon) and depends only on γ , whereas E_r depends on the surface and the geometries $(\alpha, \beta \text{ and } \gamma)$.

The relative uncertainty on E_d is around 2 %. For instance, for an angle γ of 82°,

$$\frac{u(E_d)}{E_d} = 1{,}8\% \tag{14}$$

As regards E_r , under some of the most unfavourable conditions, like $(\alpha = 1°; \beta = 105°; \gamma = 68°)$, we obtain :

$$\frac{u(E_r)}{E_r} = 3{,}3\% \text{ for the R2 sample (resp. } 4{,}7\% \text{ for the R4 sample)} \tag{15}$$

Thanks to the above evaluation of combined uncertainties, we can deduce the type B relative standard uncertainty on the luminance coefficient. We compute uncertainties on each q-value in the r-table (CIE,1984), and Table 2 presents, for both samples, the average of uncertainties on all the q-values, and the 80th and 90th percentile of uncertainties (e.g. a 3%-value at 80-percentile means that 80% of the uncertainties of the q-values in the r-table have uncertainties below 3%).

Table 2 – Relative B-Type uncertainties on q for r-table geometry

	R2	R4
Mean	2,6%	3,7%
80-percentile	3,0%	5,0%
90-percentile	3,5%	6,5%

The results are satisfactory for both samples.

4.2 Uncertainty Type A

The method of the combined standard uncertainties may not take into account some other factors like the variation of the lamp voltage supply or the impact of the sample positioning during the calibration phase and the testing phase. This latter factor is indeed crucial because the precision in positioning the sample helps to keep constant the lighted and measured area on the surface, whatever the geometry. In order to measure the impact of those factors on the uncertainty of the measurements, we therefore conducted a type A uncertainty assessment, with four measurements of reproducibility on both samples.

In the worst-case scenario of the viewing angle ($\alpha = 1°$), and for angle configurations recommended by (CIE, 1984), results obtained are summed up in Table 3.

Table 3 – Relative A-Type uncertainties on q for r-table geometry

	R2	R4
Mean	3,4%	3,6%
80-percentile	4,5%	4,3%
90-percentile	4,8%	4,9%

Type-A uncertainties are also quite satisfactory.

4.3 Global standard uncertainty on the luminance coefficient

Eventually, the expression of the standard uncertainty on the luminance coefficient takes into account the B-type uncertainty (for uncertainty sources which can be computed using our knowledge of the material) an also the A-type uncertainty. Then we propose to combine both uncertainty types to compute the standard uncertainty on the luminance coefficient (Table 4).

$$u(q)^2 = u(q)^2_{type\ A} + u(q)^2_{type\ B} \tag{16}$$

Table 4 – Relative standard uncertainty on q for r-table geometry

	R2	R4
Mean	4,4%	5,3%
80-percentile	5,3%	6,5%
90-percentile	5,7%	8,0%

The relative standard uncertainty remains under 10% for both samples at the 90-percentile, with a mean around 5%. This result is quite acceptable.

4.4 Expanded uncertainty on the luminance coefficient

The expanded uncertainty *U(q)* for a 95% level of confidence (coverage factor of 2) can be deduced from the above computations (JCGM, 2008) (Table 5).

$$U(q) = 2u(q) \tag{17}$$

Table 5 – Relative expanded uncertainty on q for r-table geometry

	R2	R4
Mean	8,8%	10,6%
80-percentile	10,6%	13,0%
90-percentile	11,4%	16,0%

The final expanded uncertainty is around 10% for both samples. This result is quite satisfactory, considering the fact that road surfaces are rough and fidelity of measurements are very difficult.

4.5 Uncertainties on Q_0 and S_1

From the global standard uncertainties on the luminance coefficients, we can deduce the uncertainty on parameters used for road lighting applications to describe the reflection properties of road surfaces, the average luminance coefficient Q_0 and the specular factor S_1 (CIE, 1984) which are defined as:

$$Q_0 = \frac{\int_0^{\Omega_0} q \, d\Omega}{\Omega_0} \tag{18}$$

where:

Ω_0 is the solid angle containing all the directions of light incidence at the considered point of the road.

and S_1:

$$S_1 = \frac{r(0,2)}{r(0,0)} \tag{19}$$

with:

$$r(\beta,\gamma)=q(\beta,\gamma).cos^3(\gamma) \tag{20}$$

Assuming our luminance coefficients are statistically independent, the combined standard uncertainty on Q_0 and S_1 is:

$$u^2(Q_0) = \frac{\int_0^{\Omega_0} u(q)^2 \, d\Omega}{\Omega_0} \tag{21}$$

$$u^2(S_1) = \left(\frac{\partial S_1}{\partial r(0,2)}\right)^2 u(r(0,2))^2 + \left(\frac{\partial S_1}{\partial r(0,0)}\right)^2 u(r(0,0))^2 \tag{22}$$

where: $\frac{\partial S_1}{\partial r(0,2)} = \frac{1}{r(0,0)}$ and $\frac{\partial S_1}{\partial r(0,0)} = -\frac{r(0,2)}{r(0,0)^2}$ (23)

Computations of expanded uncertainty (coverage factor 2) on Q_0 and S_1 are presented in Table 6.

Table 6 – Expanded relative uncertainty on Q0 and S1

	R2	R4
$U(Q_0)/Q_0$	6,4%	7,4%
$U(S_1)/S_1$	2,1%	2,5%

These uncertainties are relatively acceptable, especially considering the grazing 1° viewing angle as one of the most unfavourable geometry.

5 Evaluation of the influence of uncertainties on the quality of a lighting design

The quality of service of a lighting installation is estimated through parameters like the average luminance on the pavement $\bar{L}$, the general uniformity of the luminance U_0, and its longitudinal uniformity U_l. These parameters are determined from a model that takes into account the geometry of the installation (road type and luminaires placement), the photometry of the luminaires, and the r-table of the pavement.
In order to study the impact of the uncertainties, calculations with Dialux were conducted on a straight road (7m width) with the same lighting installation varying the r-table. For each measured road samples (R2 or R4), road luminances were computed based on:

- min_rtable: the r-table with the minimum values of the 95% confidence interval obtained for each r-value;
- ref_rtable: the measured r-table;
- max_rtable: the r-table with the maximum values of the 95% confidence interval obtained for each r-value.

The lighting installation was designed to follow the M3 Class of EN13201-2 (CEN, 2016) with luminaires on one-side of the road, with medium-expanded photometry, 10 m height, 19 m spacing, 0,2 m projection, and a maintenance factor of 0,8. Table 7 shows using the extreme r-tables (i.e. min_rtable or max_rtable) leads to a 9% relative error for the R2 sample (resp. 7% for the R4 sample) on the mean luminance of the road compared to the measured ref_rtable. Therefore, a 10% margin can be taken into account when designing a lighting installation to ensure the minimum $\bar{L}$ value. In our case study, the relative errors on uniformity parameters are less than 2%. However, further investigation is needed by exploring various lighting installations and case studies to quantify the required margin to respect uniformity requirements.

Table 7 – Dialux computations results

	r-table	Q0	S1	$\bar{L}$(relative error w.r.t the ref)	U_0 (relative error w.r.t the ref)	U_l (relative error w.r.t the ref)
R2	Min	0,055	0,469	1,17 cd/m² (9%)	0,83 (0%)	0,96 (0%)
	Ref	0,060	0,454	1,28 cd/m²	0,83	0,96
	Max	0,065	0,442	1,4 cd/m² (9%)	0,83(0%)	0,96 (0%)
R4	Min	0,071	4,082	1,67 cd/m² (7%)	0,43 (2%)	0,82 (0%)
	Ref	0,076	4,280	1,8 cd/m²	0,44	0,82
	Max	0,082	3,920	1,93 cd/m² (7%)	0,45 (2%)	0,83 (1%)

6 Conclusions

As our gonioreflectometer has been specifically designed for public lighting applications, we tackle its qualification from three different perspectives. The first one is validation of measurements thanks to comparisons with direct measurements in a few geometries, and comparisons with calculations for analytically tractable cases on a few geometries. The second one concerns calculations of uncertainties, and results obtained (around 10% of relative expanded uncertainty on the luminance coefficient) are quite satisfactory. The third one involves the assessment of the influence of this uncertainty on the quality of a given road lighting design, which is quite limited. Further work comprises intercomparisons with other laboratories that will be undertaken under the European project Surface. We will also deepen our road lighting design calculations with regard to uncertainty evaluation, and extend uncertainty computations beyond the r-table, i.e. for the whole BRDF.

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