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TABULATION AND COMPLETION OF MEASURED BRDF DATA FOR LIGHTING COMPUTATIONS

Dumont E., Joulan K., Ledoux V.
Université Paris-Est, Ifsttar, Paris, France
eric.dumont@ifsttar.fr

Abstract

This paper proposes a practical method for the tabulation and completion of measured BRDF data. The BRDF of materials is needed for lighting computations and computer graphics. It can be measured with a gonioreflectometer, but the resulting data is often irregular and always partial. A common solution to get a complete BRDF is to fit the available data with an analytical model. An arguably more accurate solution is to interpolate and extrapolate from the available data. This solution was implemented using Scilab, a free open-source software, and tested on two typical road surface materials: plain asphalt pavement and asphalt pavement painted with retroreflective marking.

Keywords: BRDF, Photometry, Lighting, Luminance, Retroreflection, Grazing Angles

1 Introduction

Global illumination techniques have achieved a high degree of physical fidelity which serves many fields of application and particularly lighting design. Some physically-based rendering engines make it possible to account for the actual photometrical properties of light sources, surface materials and even scattering media, without need for analytical models. The problem now lies in the collection of the photometrical data, especially for characterizing reflection properties, since it involves a three-dimensional function (with a fourth dimension for anisotropic materials) whereas emission involves only two dimensions, and scattering usually only needs one.

The reflection properties of a surface material are characterized by means of the luminance coefficient, which is defined as the ratio between the reflected luminance and the illuminance, at any given point on the surface (CIE, 1984). It varies with both the lighting direction and the viewing direction and is thus often referred to as the bidirectional reflectance distribution function (BRDF). It can be measured by means of a gonioreflectometer, with some limits: retroreflection directions are problematic and grazing directions are simply unattainable (Coulomb, 1996).

Once the BRDF data are collected, the problem of implementing them still remains because lighting computations will almost certainly involve directions that were not measured. The common approach consists in approximating the BRDF by fitting analytical or empirical models to the data (Lawrence, 2004). However, direct sampling of the actual data is preferable for accurate photometrical computations (Antonutto, 2004). The reflectance value for a given lighting direction and a given viewing direction can simply be linearly interpolated, provided that the BRDF data is completely tabulated (or “gridded”) – hence the need for a tool to tabulate and complete irregular and partial BRDF data before running lighting computations.

In this paper, we propose a pragmatic solution to perform these operations using Scilab, a free scientific software package which facilitates the manipulation of multi-dimensional arrays (Bunks, 1999). In the Scilab programming environment, it takes little more than 200 lines of code to turn irregular and partial BRDF data into a complete BRDF table.

Section 2 examines BRDF measurement and how to implement measured BRDF data into lighting computations. Section 3 describes the operations performed with Scilab to tabulate and complete irregular and partial BRDF data. Section 4 presents the results obtained with two road surface samples. Section 5 tackles the issue of the assessment of the proposed approach.

2 BRDF measurement and implementation in lighting computations

2.1 Definition

The reflective properties of a surface depend on the material as well as on the texture, especially for rough surfaces such as those encountered in the road environment. They are characterized by means of the luminance coefficient $q(\omega_i, \omega_r)$, which is defined as the ratio between the reflected luminance $L(\omega_r)$ and the illuminance $E(\omega_i)$, at any given point on the surface (CIE, 1984). It varies with both the lighting direction ω_i and the viewing direction ω_r as illustrated in Figure 1. It is thus often referred to as the Bidirectional Reflectance Distribution Function (BRDF).

$$q(\omega_i, \omega_r) = \frac{dL(\omega_r)}{dE(\omega_i)} \tag{1}$$

A Lambertian, or diffuse, surface reflects a constant luminance in every directions however it is illuminated. A specular, or mirror-like, surface reflects light only in the direction symmetrical to the lighting direction with respect to the surface normal (following Snell-Descartes law). Real-world surfaces generally fall between these theoretical cases. The road environment also contains retroreflective materials, designed to reflect light back where it came from in order to optimize vehicle lighting.

From this point on, we only consider isotropic surface materials. The BRDF is then independent of the lighting half-plane, and may be described with three angles: θ_i , φ_i and θ_r (with φ_i set to zero). It should be noted that this consideration is reasonable for most but not all materials in the road environment: for instance, microprism sheetings on road signs are definitely anisotropic.

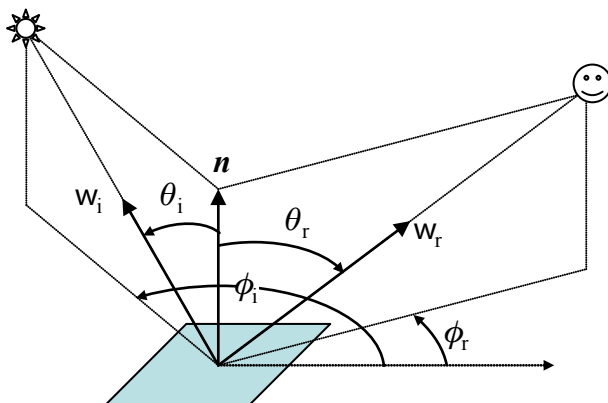


Figure 1. The BRDF is generally a function of 4 angles

2.2 Properties

The BRDF obeys two physical principles: energy conservation and Helmholtz reciprocity. The energy conservation property states that a surface cannot reflect more light than it receives. It yields the following inequality on the directional hemispherical reflectance $\rho(\theta_i)$:

$$\rho(\theta_i) = \int q(\theta_i, \varphi_r, \theta_r) \cos \theta_r d\omega_r \leq 1 \tag{2}$$

Helmholtz reciprocity principle states that the luminance coefficient stays the same when the lighting and viewing directions are interchanged. Combined with the symmetry of the BRDF about the lighting plane, it yields the following equality:

$$q(\theta_i, \varphi_r, \theta_r) = q(\theta_r, 2\pi - \varphi_r, \theta_i) = q(\theta_r, \varphi_r, \theta_i) \tag{3}$$

2.3 Measurement

The BRDF is measured by means of a device called a gonireflectometer, as it measures light reflected from an illuminated surface sample at different angles. For a thorough characterization, a gonireflectometer ought to cover a hemisphere over the sample. However, there are geometrical constraints which will prevent measurement in certain directions or combinations of directions, namely retroreflection ($\theta_r = \theta_i$; $\varphi_r = 0$) and grazing angles ($\theta_i \approx \pi/2$ and $\theta_r \approx \pi/2$, $\forall \varphi_r$).

Ifsttar's photometry laboratory owns a gonioreflectometer that was designed especially for measuring the BRDF of rough surface materials such as road pavement, with a measurement area of 10 cm in diameter (Coulomb, 1996). This gonioreflectometer, illustrated in Figure 2, was also designed for grazing lighting angles (up to 85°) and even more grazing viewing angles (up to 89°) with drivers' experience in mind. It also closely approaches retroreflection (within $2,5^\circ$). Within these limits, any list of combinations of angles may be input for measurement by the device. Results are saved to an ASCII file with a single comment line followed by 4-column data lines containing the values of the 3 angles and the luminance coefficient for each combination.

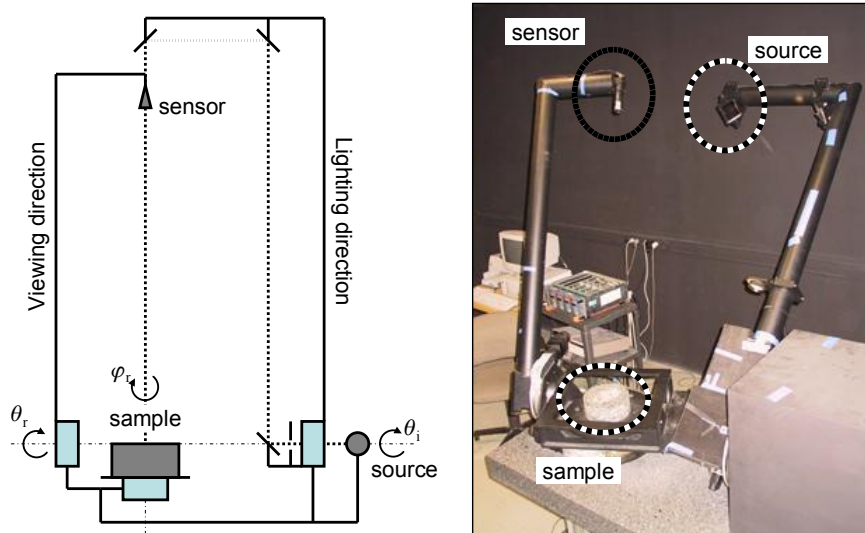


Figure 2. Ifsttar's 3-angle gonioreflectometer was designed to measure the BRDF of road surface samples

2.4 Implementation in lighting computations

The point of measuring the BRDF of a material is to calculate its luminance under various illumination and observation conditions. However, because of the geometric limits at retroreflection and grazing angles, because of possible measurement errors (due to under- or over-exposure), and simply because not all angle combinations are measured, some luminance coefficient values are unavailable in the collected BRDF data. Hence, a method is needed to determine the luminance coefficient for angles that have not been measured.

The common solution consists in approximating the BRDF by fitting analytical (theoretical or empirical) models to the data (Lawrence, 2004). However, direct sampling of the actual data is arguably preferable for accurate photometrical computations (Antonutto, 2004), especially for rough road surface materials. The reflectance value for a given lighting direction and a given viewing direction can simply be linearly interpolated, provided that the BRDF data is completely tabulated (or "gridded"). Hence the need for a tool to tabulate and complete irregular and partial BRDF data before running lighting computations.

3 Tabulation and completion of measured BRDF data

3.1 Using Scilab

Raw BRDF data measured with a (3-angle) gonioreflectometer consist in a $N \times 4$ matrix, N for the number of combinations of the 3 angles which were measured, and 4 for the dimension of the vector $(\theta_i, \varphi_i, \theta_r, q)$ containing the values of the 3 angles and the value of the measured luminance coefficient for each combination. Tabulating the raw data involves transforming this matrix into a 3D-array (one dimension for each of the 3 angles). The resulting array is sparse, and needs to be completed by means of interpolation and extrapolation, knowing that it is usually irregular. So it all comes down to manipulating multi-dimensional arrays. This analysis naturally led us to use Scilab, a free and open source scientific software package which facilitates the manipulation of multi-dimensional arrays (Bunks, 1999).

2.1 Tabulation

Tabulation is the first step. It involves browsing the data to extract the number and values of the angles θ_i , φ_r and θ_r at which the measurement were performed. It is possible to increase the size of the array by implementing the Helmholtz reciprocity principle (Equation 3), which will provide reflectance values at angles which were not actually measured. In case of duplicate combinations, the reflectance values can simply be averaged. The data are then sorted by ascending angle value, first with θ_i , then with φ_r and finally with θ_r . At this point the reflectance values are still stored in the 4th column of a 4-column matrix.

2.1 Completion

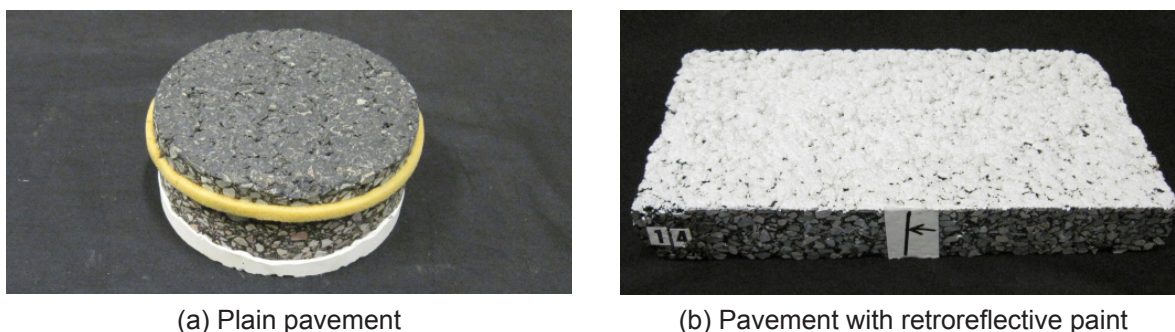
The next step consists in interpolating the BRDF values in the retroreflection directions. It can be achieved by a call to the bidimensional cubic Shepard interpolation function for each lighting angle θ_i . This is where the data are “gridded” using Scilab hypermatrices. The choice of the Shepard function was dictated by the irregular nature of the data.

The final operation consists in extrapolating BRDF values at $\theta_i = 90^\circ$, the perfectly grazing lighting angle. It can be achieved by a call to the cubic spline interpolation function. Contrary to the Shepard function, the spline function allows extrapolation, but only in one dimension for irregular data. The BRDF at the perfectly grazing viewing angle does not need to be extrapolated, because lighting computations involve $q \cdot \cos(\theta_r)$, which is null at $\theta_r = 90^\circ$.

The result is a 3D-array which can be saved in an adapted version of the Radiant Imaging BSDF data interchange file format, arbitrarily adopted for lack of a standard format. It involves calculating the directional hemispherical reflectance expressed in Equation 2. The previous operations were programmed into a Scilab script. This script contains less than 250 lines, including input/output instructions and comments.

4 Sample results

The proposed method for tabulating and completing measured BDRF data was tested on two samples of asphalt pavement, one painted with retro-reflective painting. The samples are presented in Figure 3.



(a) Plain pavement

(b) Pavement with retroreflective paint

Figure 3. Pictures of the sample road surfaces on which the BRDF was measured, and then tabulated and completed

Both rough surface samples were measured with Ifsttar’s 3-angle goniophotometer, presented in Section 2.3. The lighting angle θ_i was sampled every 10° between 0° and 80° . The viewing angle θ_r was sampled every 5° between 0° and 85° , plus 88° and 89° . The angle between the lighting and viewing half-planes φ_r was sampled every 10° between 0° and 180° , plus 2° and 5° . Raw and completed BRDF data are presented for several lighting angles in Figure 4 for the plain pavement sample and Figure 5 for the painted pavement sample. Two obvious observations can be made: the plain pavement surface is dark and shows specularly with a little retroreflectivity at high lighting angles, while the painted pavement surface is light and retroreflective, especially at high lighting angles.

To illustrate these results, lighting computations were performed with the PROF-LCPC Monte Carlo light tracing software which takes into account tabulated photometric properties of light sources, materials and scattering media (Dumont, 1999). A rural scene illuminated by headlights was simulated with analytic BRDF models for the pavement (Lambert model) and markings (Phong model adapted for retroreflectivity) and with the previously measured and completed BRDF data. The resulting luminance

maps are presented in Figure 6. It appears that the slight retroreflectivity of the pavement makes quite a difference.

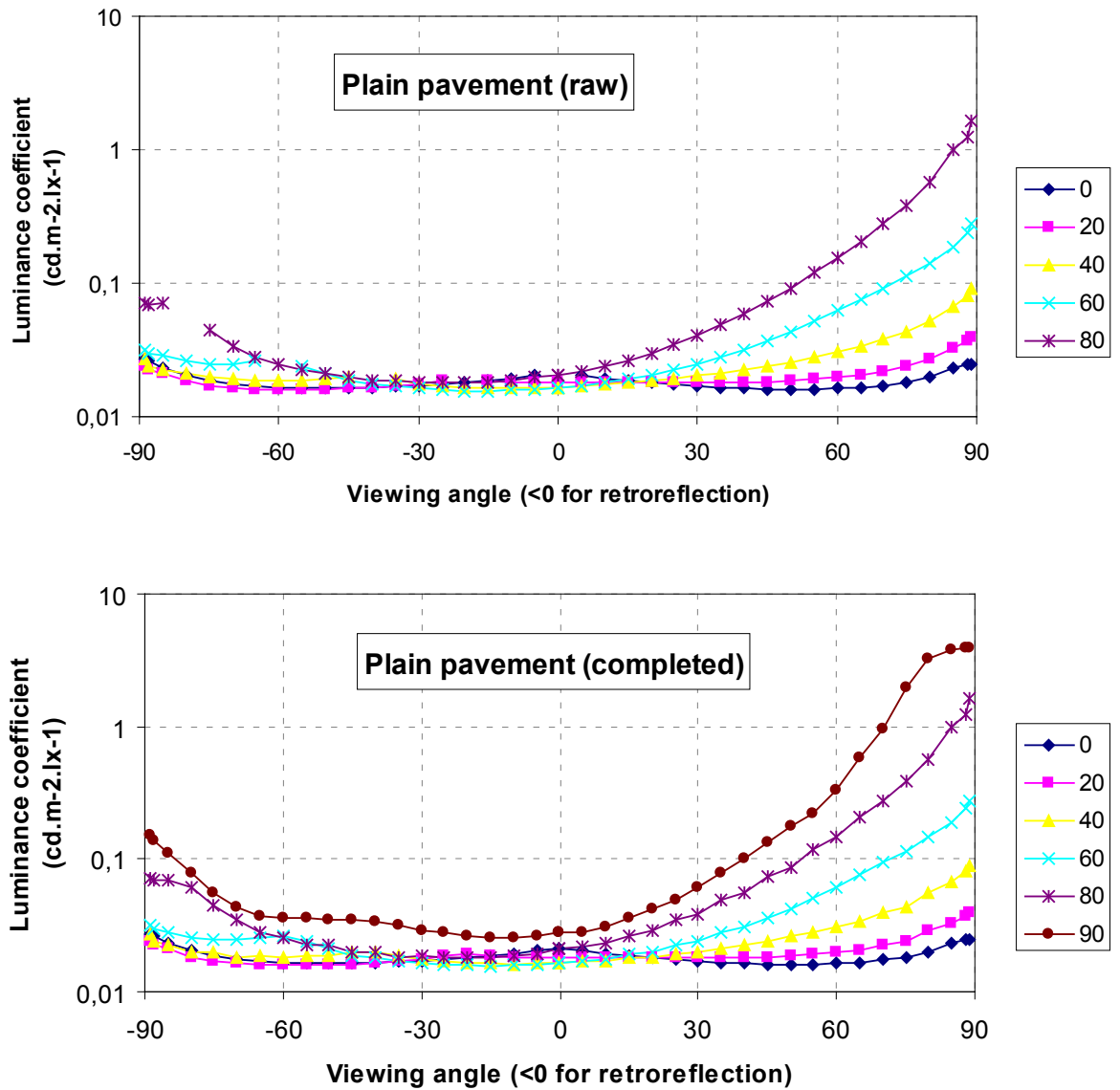


Figure 4. Raw and completed BRDF data for the plain pavement surface sample

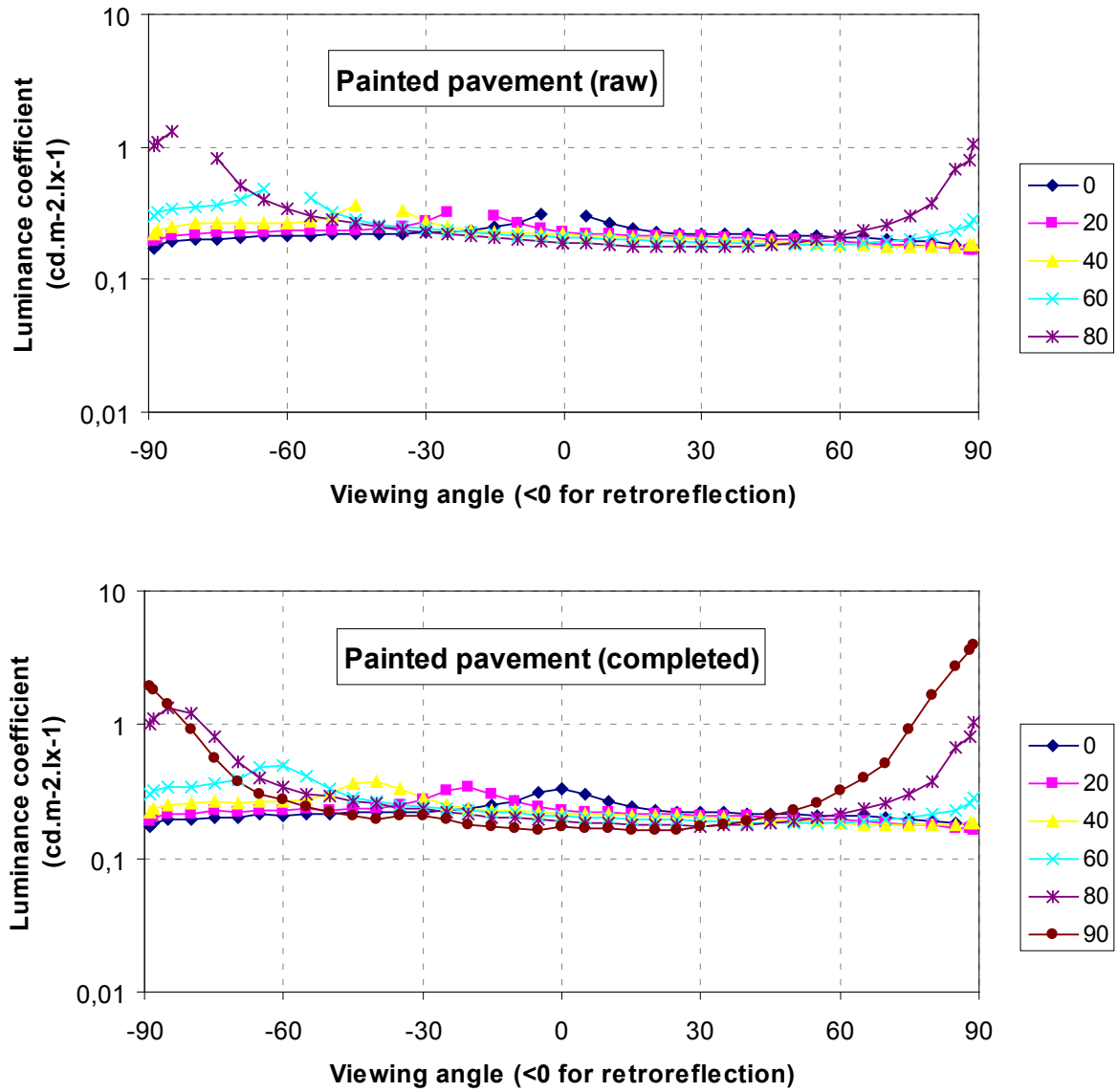


Figure 5. Raw and completed BRDF data for the painted pavement surface sample

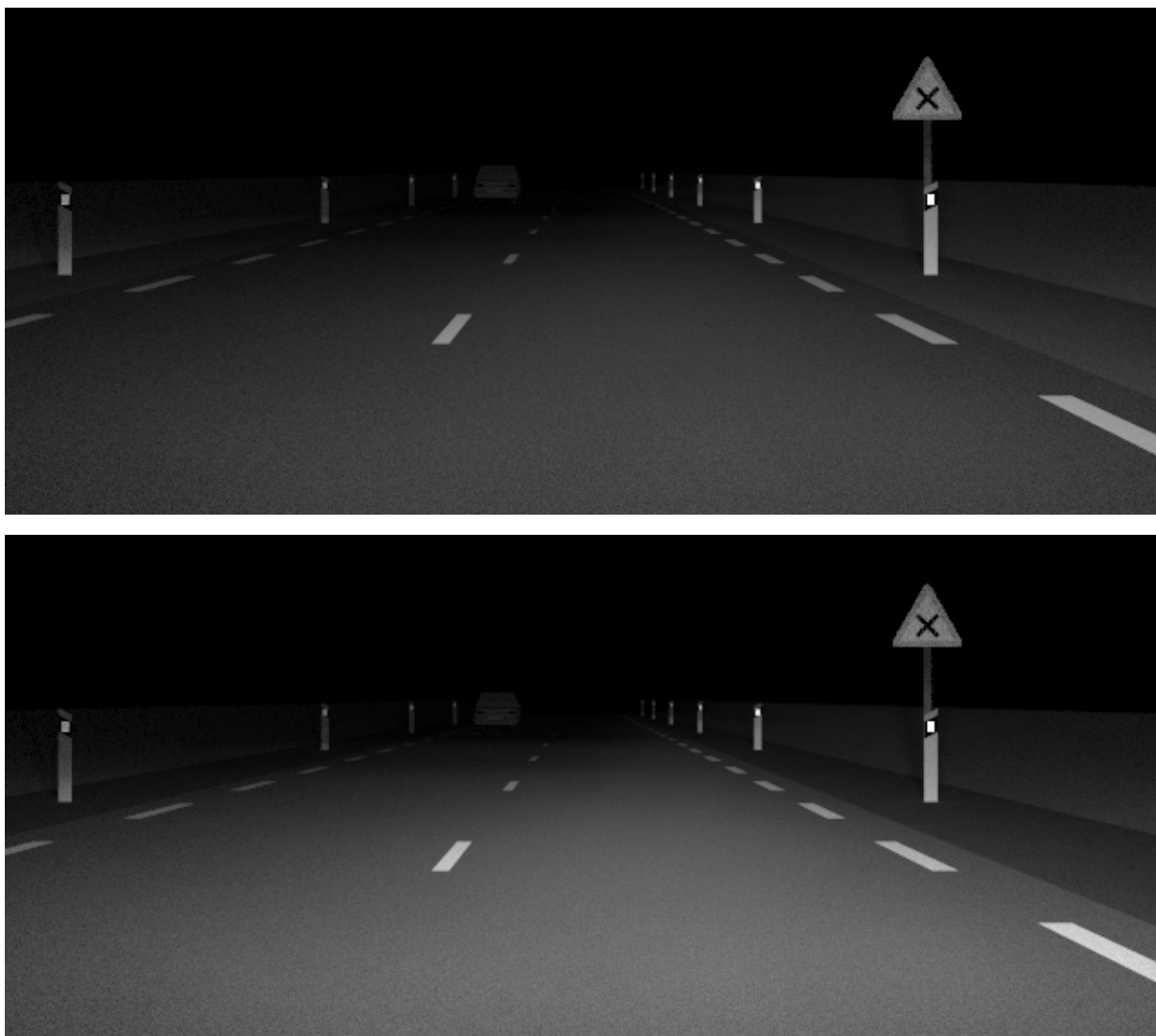


Figure 6. Luminance map of a road scene illuminated by headlamps simulated with PROF-LCPC with analytical BRDF models (top) and measured BRDF data (bottom)

5 Discussion

A practical method to tabulate and complete BRDF data measured with a 3-angle gonioreflectometer has been proposed. The resulting data facilitates lighting computations based on interpolation into the photometric data, which is arguably more accurate than using analytical models.

It should however be emphasized that the interpolation and extrapolation operations performed for the completion will result in sound data if the combinations of angles at which the measurements are made are chosen soundly. It is recommended to sample more densely at specular and retroreflection directions, and to go as far as possible toward grazing directions.

The question arises whether the practical rather than physical choice of interpolation and extrapolation functions is adequate. This was tested at Ifsttar's photometry laboratory by performing complementary measurements on the previous surface samples with a 4-angle gonioreflectometer dedicated to retroreflective materials. It was first verified that luminance coefficient values measured on both gonioreflectometer at the same angles were comparable. Measurements were then made at new angles, and compared to the results of the completion. The results, presented in Figure 7, are deemed satisfactory given the roughness of the surfaces, the grazing angles considered, and the low albedo in the case of the plain pavement material. Similar evaluations were conducted at "easier" angles and on a smooth and diffuse surface and resulted in even lower relative errors.

Just like PROF-LCPC software, the Scilab script will be distributed freely to anyone who sends a demand by e-mail to the first author of the present paper.

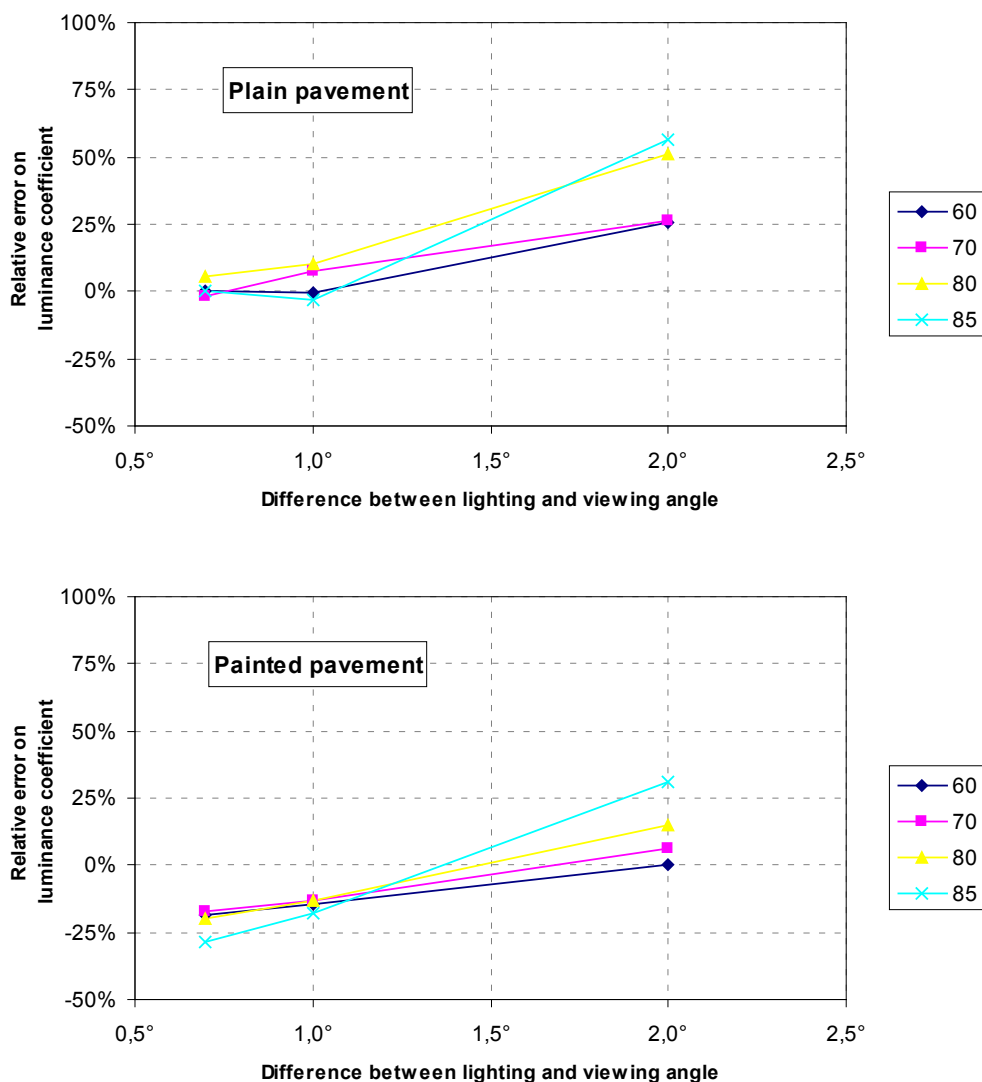


Figure 7. Comparison between measured and completed BRDF data for the plain pavement sample (top) and the painted pavement sample (bottom) at different lighting angles.

Acknowledgements

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References

ANTONUTTO, G. 2004. Road Lighting Simulation in Radiance. 3rd International Radiance Workshop, Fribourg, October 11-12.

BUNKS, C., CHANCELIER, J.P., DELEBECQUE, F., GOMEZ, C., GOURSAT, M., NIKOUKHAH, R., STEER, S. 1999. *Engineering and Scientific Computing with Scilab*. Boston: Birkhäuser.

CIE 1984. CIE 066:1984. *Road Surfaces and Lighting*. Vienna: CIE.

COULOMB, J.M., BRUSQUE, C. 1996. Propriétés de réflexion des surfaces. Le goniorélectromètre du LCPC. *Bulletin des Laboratoires des Ponts et Chaussées*, 204, 25-35.

DUMONT, E. 1999. Semi-Monte Carlo Light Tracing for the Study of Road Visibility in Fog. In *Monte Carlo and Quasi-Monte Carlo Methods 1998*. Berlin: Springer.

LAWRENCE, J., RUSINKIEWICZ, S., RAMAMOORTHY, R. 2004. Efficient BRDF Importance Sampling Using a Factored Representation. *ACM Transactions on Graphics*, 23(3), 496-505.