MEASUREMENT OF BI-DIRECTIONAL PHOTOMETRIC PROPERTIES OF ADVANCED GLAZING BASED ON DIGITAL IMAGING TECHNIQUES

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ABSTRACT

Many daylighting applications require a precise knowledge of the transmission properties of fenestration materials, called bi-directional transmission distribution functions (BTDF), which necessitate systematic and accurate measurements. A new type of bi-directional photogoniometer, based on advanced imaging techniques, has been developed to this end; its mechanical concept, the calibration procedures and the first results are presented here.

RESUME

Les applications en lumière naturelle exigent une connaissance objective et systématique des propriétés de transmission lumineuse des systèmes de fenêtres, appelées fonctions de distribution bidirectionnelles de transmission (BTDF). Un nouveau type de photogoniomètre bidirectionnel, basé sur des techniques d'imagerie numérique, a été développé; sa conception mécanique, les procédures de calibrage et les premiers résultats obtenus sont présentés ici.

INTRODUCTION

In order to reduce energy consumption and improve visual comfort, the daylight distribution inside buildings has to be optimised. However, the light behaviour expectations can only be considered with a full knowledge of the photometric characteristics of daylighting systems, like solar blinds or advanced glazing for instance. This information allows finding the judicious combination of materials adapted to the situation, already at the project's level, with an adequate idea of the system's potentialities for light deviation and energy savings. Furthermore, daylighting calculation programs also need a reliable data set of photometric measurements to be able to validate the simulations.

Precise and objective measurements of the photometric properties have therefore to be handled to control the daylighting performances of the building, with a characterisation of the element by its bi-directional transmission distribution function (BTDF). This function, also called q, is defined by relation (1) and illustrated in Figure 1:

$$BTDF(\theta_1,\varphi_1,\theta_2,\varphi_2) = q(\theta_1,\varphi_1,\theta_2,\varphi_2) = \frac{L_2(\theta_1,\varphi_1,\theta_2,\varphi_2)}{L_1(\theta_1,\varphi_1)\cos\theta_1 d\omega_1} = \frac{L_2(\theta_1,\varphi_1,\theta_2,\varphi_2)}{E_1(\theta_1)}\left[\frac{cd}{m^2 lx}\right] \quad (1)$$

where
- (θ_1, φ_1): Polar co-ordinates of incoming light flux [rad]
- (θ_2, φ_2): Polar co-ordinates of emerging (transmitted) light flux [rad]
- $L_1(\theta_1, \varphi_1)$: Luminance of element of incoming light flux [cd m^{-2}]
- $L_2(\theta_1, \varphi_1, \theta_2, \varphi_2)$: Luminance of emerging (transmitted) element of light flux [cd m^{-2}]
- $d\omega_1$: Solid angle subtended by incoming light flux [sr]
- $E_1(\theta_1, \varphi_1)$: Illuminance on sample plane, due to incident light flux [lx]

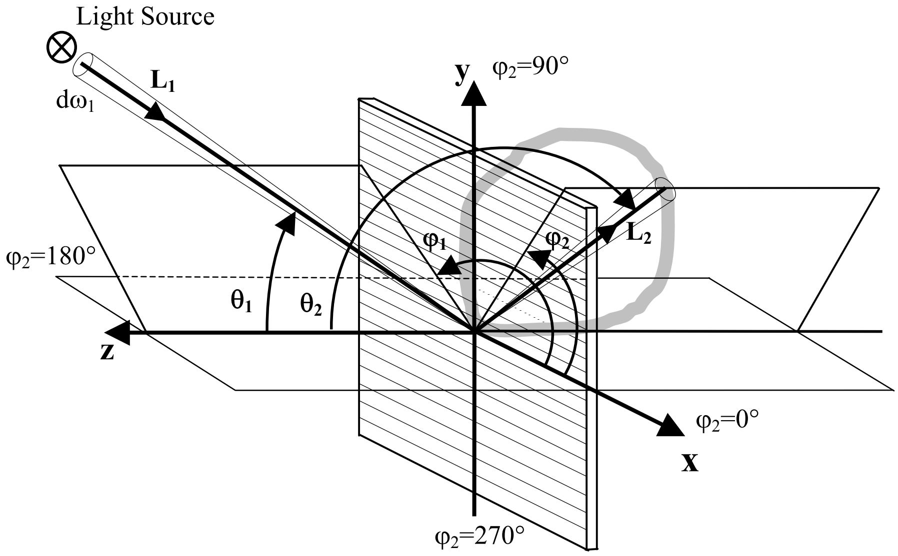

Figure 1: Photometric and geometric quantities used for BTDF definition.

Bi-directional photogoniometric devices have recently been developed to measure BTDFs [2, 3, 4, 5]. The conventional photogoniometer principle consists of a movable photometric sensor measuring illuminances in different directions (θ_2, φ_2), which leads to the associated transmitted luminances $L_2(\theta_1, \varphi_1, \theta_2, \varphi_2)$. This kind of method has the disadvantage of being highly time-consuming and problematic for emerging light beams with high gradient.

To overcome these difficulties, a new type of photogoniometer has been devised, using advanced digital imaging techniques. In this paper, we present the experimental method, give the first results obtained and consider the further development possibilities.

METHOD

Equipment description

The photogoniometer, represented in Figure 2, is composed of a movable mechanical support, presenting two main rotation axes that are powered by DC motors. It uses an accurate and reliable gear technology (harmonic drives) and is controlled by a microcomputer. The light source is placed 6 meters above. It consists of a short-arc discharge lamp (2.5 kW HMI) combining high luminous efficiency (96 Lumen / Watt) with a daylight-close spectrum (5600 K); it is placed in a floodlight projector equipped with a hyperbolic mirrored reflector, Fresnel lens and an optical conic element to enhance beam uniformity. High illuminance uniformity is observed on the sample (better than 3%).

A calibrated CCD camera, used like a multiple points luminance-meter, is pointed towards a triangular screen, painted with a spectrally neutral diffusing white paint (LMT photometer paint), and covering 60° in azimuth (see Figure 3B). The CCD camera (Kappa CF 8/1 DXCair, providing images of 752 x 582 pixels) is computer-controlled (IMAGEPRO PLUS® software) and offers integration times from 100µs to hours; the lowest integration time used is 40ms, to integrate the light source frequency modulation effects. The diaphragm aperture is set manually; a conic cap is fixed on the main platform (around the camera and the screen) to avoid parasitic light. The measurements are performed in a 5m x 5m x 8m dark room.

The rotation of the main platform (θ = 0° to 90°) and the sample holder (φ = 0° to 360°) determine the incident beam direction (Figure 3A); six positions of a 360° rotating ring, moving underneath the main platform (Figure 2), on which the camera and the screen are fixed, leads to a visualisation of the complete transmission hemisphere (Figure 3B), without any inter-reflections. The driving software has been developed in VISUAL BASIC® for a fully automated sample characterisation. Only about 2 to 4 minutes are necessary to achieve a set of BTDF data for one incident direction, against hours for classical photogoniometers.

Figure 2: Bi-directional photogoniometer developed at LESO-PB/EPFL. The CCD camera (absent on the picture) is fixed on the rotating ring at the cross mark.

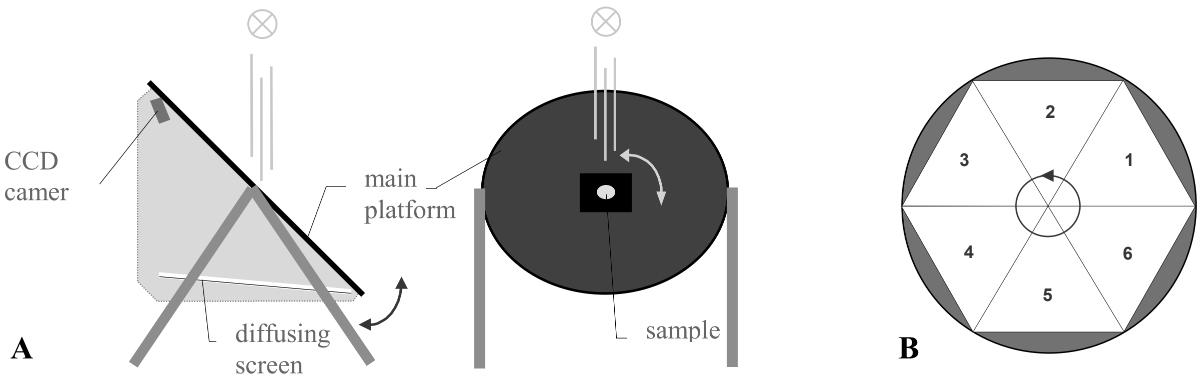

*Figure 3: **A** Rotation of main platform and sample holder. **B** Rotation of lambertian screen.*

The sample holder allows free sample sizes, with a maximum size of 40cm x 40cm. A set of diaphragms is used to limit the measured area to 10, 17, 24, and 30cm diameter; sample size and angular resolution are inversely proportional, as a consequence of a growing error in the outgoing direction when the sample size increases.

Calibration procedures

The main calibrations to achieve concern the CCD camera. The relation between the image pixels and the direction (θ_2, φ_2) associated has to be determined (geometric calibration); as the camera is used like a luminance-meter, it has to be calibrated spectrally, that is, its spectral sensitivity has to be close to $V(\lambda)$, the human eye spectral sensitivity (spectral calibration); finally, grey levels have to be converted into luminance values, and these conversions depend on the integration time (photometric calibration).

To achieve the geometric calibration, a map showing different points of known altitude θ_{2i} and azimuth φ_{2i} (901 points, i.e. every 2.5° in both directions) is drawn on a screen of same thickness and size as the diffusing one. These points are located on the digital image and the corresponding pixel co-ordinates registered; an interpolation is then applied to associate an angle couple to each pixel. This method allows taking image distortions into account without any additional correction factor.

To spectrally calibrate the CCD camera, its spectral sensitivity is determined experimentally; a least-square method is then applied to find out what kind of optical filters are adapted to correct this sensitivity in order to make it best fit $V(\lambda)$. Once these filters are chosen and cut at the right thickness, they are placed in front of the lens to achieve a quasi $V(\lambda)$ response. The curves are shown in Figure 4A [1].

For the photometric calibration, the relations between grey levels and associated luminance values are determined for each used integration time, by simultaneous measurements of a screen illuminated by a halogen light source placed at different distances from it, with the CCD camera and a calibrated luminance-meter. This conversion is illustrated by Figure 4B; the non-linear response curve is chosen to have a good resolution with low luminance levels.

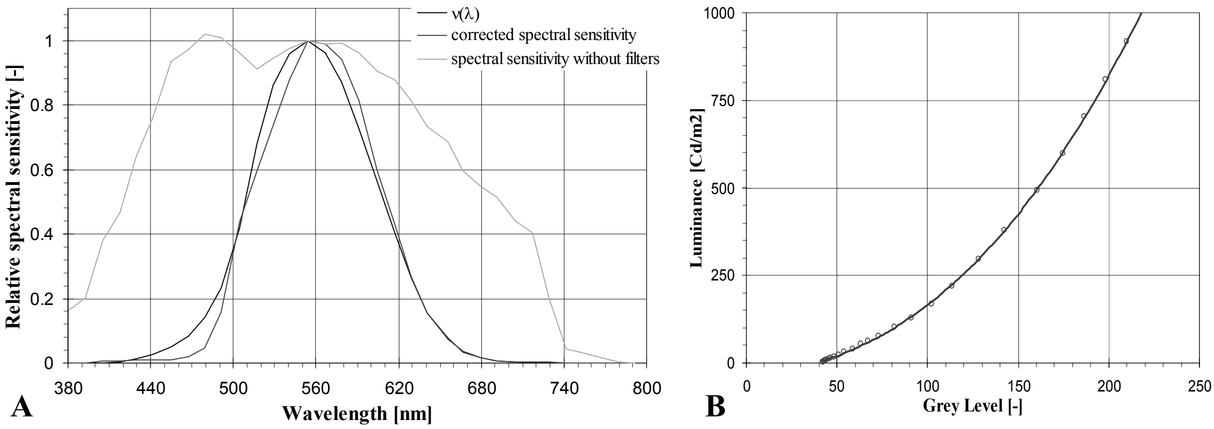

*Figure 4: **A** Spectral calibration. **B** Photometric calibration for an integration time of 40ms.*

Image and data processing

The general concept of the image processing is to improve luminance resolution and to avoid saturation and under-exposure effects by an automated selection of several integration times, followed by a superposition of image parts of appropriate luminance dynamics. For each of the six screen positions, pictures are taken with different integration times, enough to avoid under-exposure with the highest one and saturation with the lowest one. All these images are calibrated with the appropriate grey level to luminance relation, converted into 32 bits (floating point) images and divided by the simultaneously measured illuminance on sample plane $E_1(\theta_1,\varphi_1)$: their pixel values are then ratios of "screen" luminances L_{screen} and sample plane illuminances E_1; in a brightest to darkest order, the images will have their over-exposed and already treated (by a higher integration time) pixels nullified, and will then be added to form a complete calibrated 32 bits image. On these final images, pixel values are averaged to meet a certain angular discretisation grid, chosen by the user, for example each 5° in altitude and azimuth (i.e. $\Delta\theta_2 = \Delta\varphi_2 = 5°$); the obtained values are analytically converted into BTDF values (coming out from the sample centre) through relation (2). The six calibrated images created for the six screen positions are recomposed to build an image showing a hemispherical view of the whole transmission (see Figure 5A).

$$BTDF_{centre}\left[\frac{cd}{m^2 lx}\right] = \frac{\pi}{\rho} \cdot \frac{d^2(e,\theta_2,\varphi_2)}{A \cdot \cos\theta_2 \cdot \cos\alpha} \cdot \frac{L_{screen}}{E_1} \qquad (2)$$

where

- ρ: Reflection factor of triangular screen [-]
- d: Distance from sample centre (output interface) to screen along direction (θ_2,φ_2) [m]
- e: Thickness of sample [m]
- α: Angle between normal to screen and direction (θ_2,φ_2) [rad]
- A: Area of sample [m^2]

The BTDF values are saved in an ASCII file containing also the sample characteristics and the integrated light transmittance T(θ_1, φ_1), calculated from the BTDF values through relation (3):

$$T(\theta_1,\varphi_1) \approx \Delta\theta_2 \cdot \Delta\varphi_2 \cdot \sum_i BTDF(\theta_1,\varphi_1,\theta_{2i},\varphi_{2i}) \cdot \cos\theta_{2i} \cdot \sin\theta_{2i} \qquad (3)$$

RESULTS

As mentioned above, the six calibrated images are used to create a hemispherical view of the transmitted light (Figure 5A). The set of BTDF data is treated by MATLAB® (v.5.2.1.1420) to provide graphical results; examples are shown in Figures 5B, 5C, and 5D for different representations of the transmission through a 3M prismatic film under normal incidence. Figure 5B represents BTDF values by a projection on a virtual transmission hemisphere, with a colour scale proportional to the BTDF values; figure 5C shows the photometric solid (same colour scale), built in spherical co-ordinates. For both graphics, the viewpoint is freely chosen by mouse clicking. Figure 5D gives section views along C planes (perpendicular to sample plane); this representation gives a better idea of the numeric values of BTDFs.

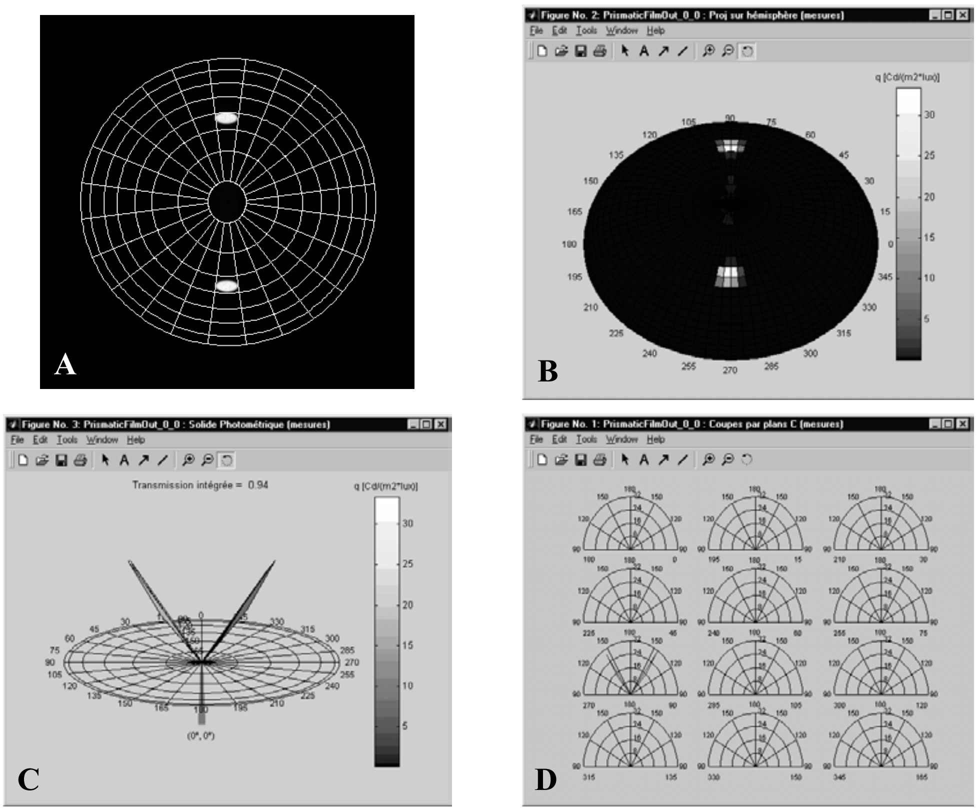

*Figure 5: **A** Calibrated image recomposed from sixths. **B** Hemispherical projection. **C** Photometric solid. **D** Section views along C planes.*

Validation

As most bi-directional photogoniometers are still under calibration or testing stages, there is no extended BTDF data set accurate enough to be taken as a reference. The validation possibilities are therefore of different kind: a) comparison with analytically expressed BTDF values, in well-known situations (like a hole, or a lambertian sample), b) comparison of integrated BTDF values and transmittances measured with integrating spheres for the same material [2], c) comparison of BTDF values measured with different photogoniometers on the same sample [2].

The first two possibilities have been applied on our earliest results; the differences are in general lower than 10%, which is very promising. The third possibility will be applied as soon as a larger data set will be available.

CONCLUSION

This new type of bi-directional photogoniometer has been tested successfully and the advanced imaging techniques have proven their usefulness to accelerate scanning and improve luminous resolution. The difficulty lies in the high quality calibration of the camera, in order to convert it into a reliable geometrically calibrated multiple points luminance-meter.

Several daylighting activities will certainly take benefit from precise and objective characterisation of fenestration components, which can lead to a better use of these elements in building construction, and to bring progress in research and industrial applications. Further developments combined with the creation of a BTDF data set for a statistically valid number of fenestration materials could allow classifying them into certain typical transmission figures (specular, diffuse, etc…) and providing a catalogue of market products used by architects and industrials. A possible way to improve the data treatment could be the use of spherical harmonics to reduce the amount of data, by approximating them by Legendre polynomials.

ACKNOWLEDGEMENTS

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REFERENCES

1. Andersen, M.: Dispositif de mesure de la luminance du ciel basé sur des techniques d'imagerie numérique […]. Travail de diplôme DP/EPFL, Lausanne, 1998.
2. Aydinli, S.(ed.): IEASHC Task21 Report on physical quantities to be measured in laboratory facilities. Technische Universität Berlin, Berlin, 1997.
3. Bakker, L. et al.: Measuring and processing optical transmission distribution functions of TI-materials. TNO, Delft, 1995.
4. Papamichael, K. et al.: Determination and Application of Bidirectional Solar-Optical Properties of Fenestration Systems. Lawrence Berkeley Laboratory, CA, 1988.
5. Rosenfeld, J.L.J.: The new Cardiff goniometer to measure the detailed optical properties of advanced glazing units. University of Wales, Cardiff, 1997.
6. Scartezzini, J.-L. et al.: Bidirectional photogoniometer for advanced glazing materials based on digital imaging techniques. Lighting Research and Technology (29), 1997.