Combining time-efficient goniophotometry with scale model studies in a unique instrument

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1. Introduction

For the last two decades, advanced lighting strategies have been developed to reduce a building's environmental impact by combining natural and electric lighting adequately while improving the visual comfort of users. These strategies also include the minimization of heating and cooling loads through a more efficient control of daylight and solar radiation.

To achieve a better understanding of the sunlight behavior inside a given building, scale models can be used and the sun course simulated by fixing it on a heliodon. On the other hand, the development and performances optimization of advanced fenestration systems or luminaires require an accurate characterization of their components, and more specifically ask for a detailed assessment of their reflection or transmission properties.

To answer these issues, a new measurement device for the in-depth investigation of the light distribution within buildings is being developed, whose aim is on one hand to assess the sunlight distribution inside scale models of buildings or rooms, and on the other hand to achieve truly time-efficient bidirectional goniophotometric measurements of coatings or materials. The types of materials expected to benefit from this detailed characterization are typically the ones used for complex fenestration systems such as novel solar blinds, new glazing or coating materials, sunlight and daylight-redirecting devices, as well as the many types of reflectors used in luminaires.

The intuitive but time consuming scanning-based (point-by-point) analysis adopted by most of the goniophotometers so far [1][2][3][4], that use a movable photo-sensor to track and measure in all possible directions the outgoing luminance of the light flux emerging from the sample, has prevented extensive BTDF or BRDF databases to be available for manufacturers. In addition to the time-consumption problem, worsened if a fine spatial resolution is wanted, the risk of missing a narrow light peak with a large gradient in the space left between two measurement points can never be avoided. Materials with a high dynamical luminance range can thus cause serious technical difficulties, and require local refinements of the angular resolution as well as a preliminary characterization.

To overcome these problems, the resort to digital imaging techniques combined to a projection principle was adopted for the video-goniophotometer recently developed at the Solar Energy and Building Physics Laboratory (LESO-PB) at EPFL (Swiss Federal Institute of Technology) [5][6]. Its functioning principle is based on the projection of emerging light on a diffusing screen before being detected by a calibrated, digital video-camera, used as a multiple-points luminance-meter. It successfully answers the above-mentioned issues by

allowing a much higher time-efficiency in characterizing the bidirectional photometric properties of whole fenestration systems (a few minutes per incident direction instead of several hours for conventional approaches), and in offering a continuous investigation of the emerging light distribution, only limited in resolution by the pixels of the digital images themselves. The use of digital imaging also allows material samples showing large range of luminances to be analyzed without any loss of accuracy, while offering an appreciable flexibility in the data processing.

The instrument proposed here also relies on digital imaging techniques for time-efficiency but resorts to a mirror-projection principle so as to reduce the measurement time even further and will provide not only photometric (i.e. integrated over the range of wavelengths to which the human eye is sensitive) functions but also the spectral properties of transmitted and reflected light.

2. Description of the instrument in its goniophotometer configuration

The instrument relies on a principle similar to the one imagined by Ward in 1992 for computer graphics applications [7]: measurements will be performed by collecting the light flux emitted by a sample on a half-mirrored hemi-ellipsoid (the sample being placed at one of its focal points), that redirects the light towards the second focal point, where a CCD camera is placed, equipped with a fish-eye lens (see Picture 1). While the original concept dedicated to computer renderings only allowed reflection measurements, this instrument will be able to provide both the bidirectional transmission (BTDF) and reflection (BRDF) functions of the considered materials. This will be achieved in a continuous way, even for samples showing strong gradients in luminance.

But on top of these capabilities, it will be possible to cover the whole solar spectrum with a wavelength-dependent investigation. Today, no experimental equipment suitable for daylighting applications is capable of answering requirements both in time-efficiency and completeness of information (transmission, reflection, spectral), which places this research in a leading position. Using a set of filters in front of the light source, it will be possible to determine the spectral distribution of the emerging light as well over the whole solar spectrum, which will allow going further in the materials' investigation by integrating the thermal aspects of solar radiation.

Having access to the directional properties of solar heat gain will open up unexplored design alternatives in the management of a building's thermal mass to optimize its response to solar irradiation. For instance, knowing that 70% of the direct solar heat gain will be directed upwards rather than downwards for a specific glazing material will help the designer select appropriate materials for the ceiling and floor, typically heavier ones for the former and lighter ones for the latter if a heat storage is wanted, thus refining the distribution of thermal mass and increasing the efficiency of passive heating and cooling strategies.

The considered materials will be innovative materials or coatings used for solar shading or daylight redirecting systems, or of electric lighting components like luminaires' reflectors. Examples of such materials are: diffusing materials (opalescent plastics, diffusing paints), light redirecting components (laser cut panels, glass or acrylic structures embedded in double glazing, holographic films, mirrored surfaces), prismatic panels or films, fabrics with or without a reflective coating, venetian blinds of different profiles and coatings, micro-structured reflectors, etc.

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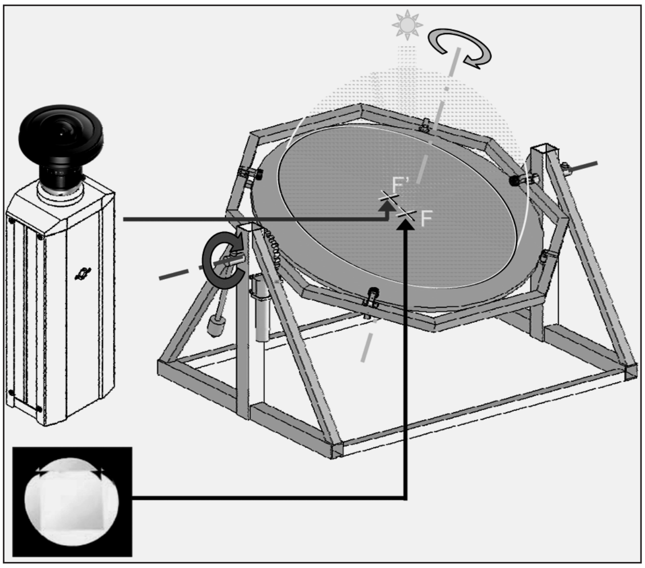
This instrument is expected to be complemented by ray-tracing simulations for the characterisation of whole daylighting systems or luminaires, restricting the measurements to their components and allowing flexibility and adjustment possibilities by integrating the geometry and arrangement options to the computer-based approach. Combining experimental and ray-tracing based results to determine the transmission and reflection properties of advanced glazing and shading systems has already shown great potentialities for providing bidirectional data at both the level of materials and coatings and of full window or luminaire assemblies, as demonstrated by the close fit between physical and simulation-based bidirectional data for samples as complex as prisms and mirrored venetian blinds [8][9].

2.1 Functioning principle

As illustrated in Picture 1, the light flux received by the sample from the light source is be reemitted (after either reflection or transmission) towards the interior (mirror) side of the semi-transparent hemi-ellipsoid so as to be reflected towards a calibrated camera equipped with a fish-eye lens. The sample is positioned at one of the focal points (F, center of the platform), and the camera at the other (F').

This measurement principle allows the complete emerging light distribution to be captured in a single image. For BTDF measurements, the instrument is turned upside down from its configuration in Picture 1, which means that the camera will be obstructing the incident light for a small range of azimuth angles. For the few cases where the sample's heterogeneity makes this critical, it should be rotated 90° on its holder to fully characterize it within the missing angular range.



Pict. 1. Conceptual sketch of the bidirectional video-goniophotometer, with sample positioned at focal point F and camera with fish-eye lens at focal point F'.

2.2 Light detection

The hemi-ellipsoidal shell used for goniophotometric measurements must be semi-transparent (mirrored on the inside only) so as to let the beam coming directly from the light source reach the sample, even in reflection mode (see Picture 1). Also, it must keep the light flux reemitted from the sample (after either transmission or reflection) inside the shell, so that it is reflected once before being detected by the camera through its fish-eye lens. This avoids the otherwise inevitable blind spot in detection around the incident direction and enables the whole emerging space to be investigated within a single image capture.

The camera must be calibrated as a luminance-meter and the emerging directions be identified as image pixels. Even though its calibration will be more complex [10][11][12], a color camera will be preferred to a black and white one to point out occurrences of color separation (observed for holographic films and prismatic elements e.g.) and to account for both the visual performance and agreeableness factors more efficiently [13]. Also, this will allow having only one camera for scale model simulations and goniophotometric measurements.

By taking advantage of digital imaging potentialities, and in particular of the possibility of capturing several images of the same luminous situation but at different integration intervals, it has been proven for different other photometric equipments resorting to digital imaging that very large dynamics in luminance can be assessed with constant accuracy; at the same time, a high quality of measurements can be maintained for low luminance investigation as well as strong peaks in transmission or reflection, even if they are close to each other. Indeed, individual 8 bits images can be combined to form a complete 32 bits floating point image, whose pixels are thus each calibrated according to the most suitable integration time specifically.

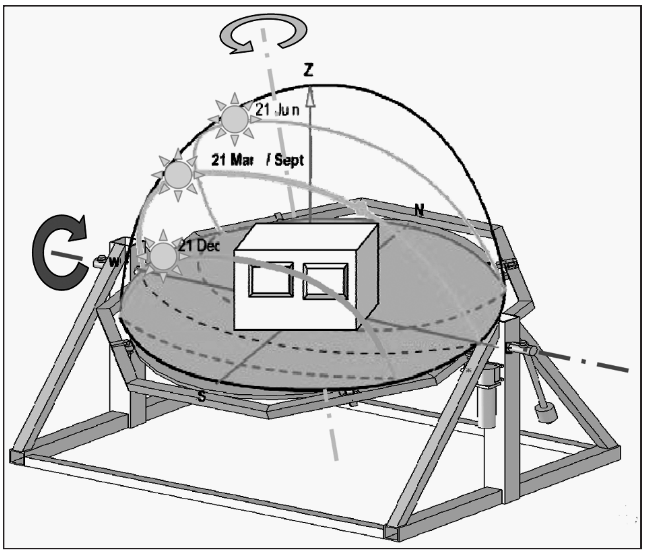
3. Description of the instrument in its heliodon configuration

To study a scale model's response to the very variable nature of sunlight, sun course simulators (heliodons) are used that generally consist of a supporting platform and a light source, either one being rotated around the scale model's centre to reproduce a specific sun course pattern depending on the location and the time of the day. Most of these heliodons are manually driven, making the simulation process quite slow and requiring a lot of human input.

The approach chosen here is fully automated and computer-driven, the scale model just needs to be fixed properly on the platform and the user will be able to choose to simulate any day of the year for any location on the earth and any orientation of the building (see Pict. 2), and get to visualize how sunlight penetrates the building over a whole day (or specific moments) in a continuous, immediate and dynamic way.

Different visualization options will be possible, including digital image capture with a color camera and either the fish-eye or an endoscopic lens to capture images inside scale models. The idea is to recreate a day passing at the location where the project is meant to be built, and try out several alternatives in building orientation, openings position and size, spaces arrangement and surface colors to find an optimum.

To simulate an impinging sunlight direction, the platform is rotated around two axes, one for the elevation of the sun



Pict. 2. Conceptual sketch of the sun course simulator (heliodon).

and one for its azimuth angle, the light source used for the sun remaining fixed and the movements being computer-driven. To simulate a full sun course, such movements are iterated in a smooth and chronological sequence.

For both applications, the light source must present spectral and collimation properties similar to the sun's. However, for scale model measurements, where the illuminated area is very large (about 1.5 m in diameter), the collimation is not as critical because the light distribution assessment will be mainly qualitative: attaining sharp shadows is sufficient.
As the desired illumination areas are so different between the scale model and goniophotometer configurations, two light sources should be used, preferably employing Xenon bulbs due to their close match to the sun's spectrum.

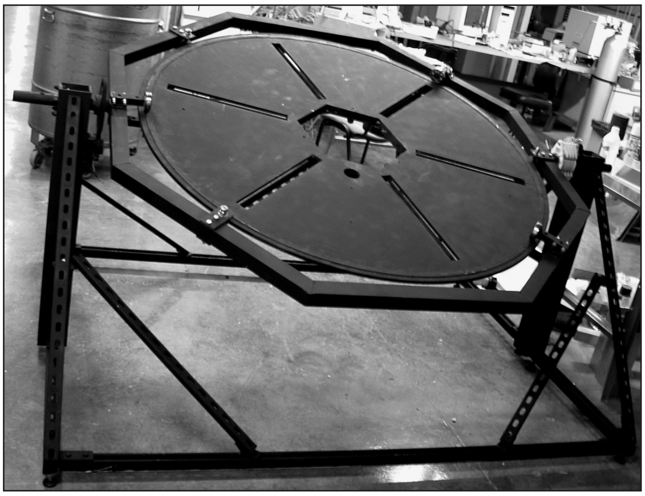
4. Characteristics of the main components

Because of its dual applicability, the rotating platform has to answer several functionality constraints, such as:

- both the scale model and sample holder must be centered on the normal rotation axis of the platform, and the horizontal axis must be in the sample plane;
- the supporting table must provide a flat basis on one side;
- a flexible fixing system must be designed to hold the scale model's base tight to the platform on its flat side, the base being of variable dimensions depending on the model;
- full access to the sample (and the camera) must be possible from the other one side of the platform;
- the sample holder must accommodate samples of varying dimensions (probably between 50 mm and 200 mm in diameter, thickness less than 20 mm).
- the conversion from scale model mode to BT(R)DF mode must be as easy as possible

4.1 Rotating platform

Two major structural elements make up the heliodome's platform, shown on Picture 3: an octagonal frame made of 8 identical hollow aluminum tubes of square section, welded together, that rotates around the horizontal axis and the 1.5 m diameter disk, supported by the frame thanks to three sets of rollers including ball bearings and rotating around its normal by the way of peripheral gears.
The disk consists of an assembly of a hexagonal frame made out of Unistrut® rails and of a set of 6 curved trapezoidal pieces of aluminum honeycomb.



Pict. 3. The Heliodome's rotating platform

Samples are to be fixed inside its open center for goniophotometric measurements, held in place by a pair of diaphragms of various aperture diameters (10, 20, 50, 100 and 150 mm) to cope with the range of possible sample sizes. As the diaphragms cannot be more than 1 mm thick because shadows would become significant at grazing angles, a second pair of thicker diaphragms is added on top and bottom of the thinner ones for reinforcement, presenting apertures large enough to avoid producing shadows on the sample. The choice of diaphragm diameter depends on both on the sample size and on the type of measurements conducted (transmission (BTDF) or reflection (BRDF) measurements) and restricts the sample's illuminated and light emergence surfaces (different only in transmission mode) to defined areas. Typically, BRDF measurements are made on sample areas of 10, 20 and 50 mm in diameter depending on the sample's heterogeneity, and BTDF measurements for the maximum illuminated area (150 mm) and a smaller light emergence area so as to allow internal reflections and scattering effects over a significant area while observing them from a small surface.

4.2 Semi-transparent hemi-ellipsoid

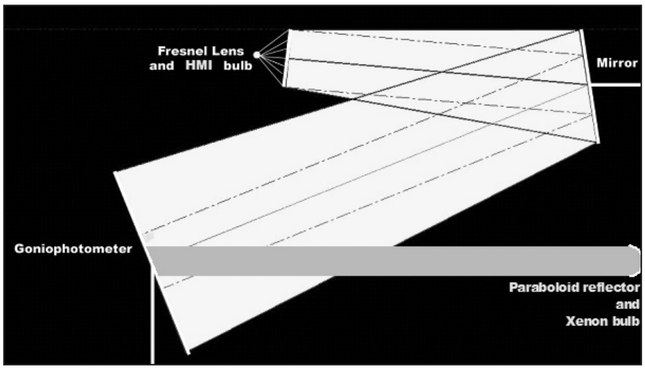
The geometry of the ellipsoid is based on a compromise between several factors:

- its dimensions are restricted by the platform's diameter;
- it has to be large enough to ensure that the travel distance of the emerging light rays from the sample to the camera is longer than 5 times the diameter of the sample (considered as an emitting point);
- the distance between the two focal points F and F' must be at least 0.2 m to avoid any overlap between the sample diaphragms system and the fish-eye lens;
- the height of the hemi-ellipsoid, which is half its minor axis, must be minimized to allow data collection in transmission mode (platform rotated by 180°) and for ease of fabrication (the larger the minor axis, the more difficult it is to make the shell by thermoforming as plastic will be "pulled" on a mould until reaching its height.

Based on these criteria, optimal interior dimensions of 1200 mm (major axis) x 1183.2 mm (minor axis) with a height of 591.6 mm were calculated

4.3 Illumination system

As the desired illumination areas are different between the scale model and goniophotometer configurations, two light sources are used.
For the scale model configuration, the HMI 1.2 kW Mole-beam projector manufactured by Mole-Richardson is used. It comprises a reflector and a Fresnel lens of diameter 460 mm (18"), and presents a color temperature of 5600°K, which is appropriate for simulating sunlight. The beam spread is set to 5° and gets reflected on a round mirror of diameter 915 mm (36") so that it illuminates the whole 1.5 m platform, as illustrated in Picture 4. The mirror reflection is required to increase the beam's travel distance, thus allowing the illuminated area to be sufficiently large with a 5° beam spread. The components' specific positioning and sizing was determined by the matrix method used in geometrical optics [14] and an optimization calculation made in Microsoft Excel® accommodating the constraints imposed



Pict. 4. Light beam adjustments in both configurations

by the dimensions of the black room and its cumbersome ceiling fixtures.

The second source, used for goniophotometric measurements, has to fulfill more severe requirements regarding its spectral and collimation properties. It therefore consists of a Xenon bulb to ensure a close match to the sun's spectrum, placed at the focus of a mirrored paraboloid reflector so as to collimate the emitted light accurately. It is positioned below the mirror, at the height of the Heliodome's horizontal rotation axis so as to illuminate the sample directly (see Pict. 4).

4.4 Light detection

To cover the visible range, the computer-commanded, digital color camera Kappa® DX 20 N (CCD sensor: $^1/_2$", 1384 x 1032 pixels, 12 bit digital system) is used.

For goniophotmetric measurements, it is equipped with a fish-eye lens manufactured by Fujinon® and presenting an opening angle that can reach 185°. In this configuration, it is placed accurately at the focal point F'.

As CCD sensors (silicon detectors) are only sensitive up to 1100 nm, a second camera will be needed to cover the IR range up to about 2200 nm, which is the limit of the most significant part of the solar radiation's spectrum. Although a lot of research has been done on calibrating CCD cameras for photometric applications, the state of the art in calibrating IR cameras for converting them into photo-sensors is very incipient, which will require fundamental research.

The chosen endoscope for scale model interior visualization is of diameter 10 mm and length 450 mm, and provides a field of view of 55° opening angle, adjustable thanks to a 90° mirror tube and zoom accessories. Whenever wide-angle images are needed, it is to be replaced by the fish-eye lens.

5. Conclusion

The current development of an original, leading-edge and time-efficient measurement device for bidirectional distribution functions is proposed presented in this paper, relying on digital imaging techniques and resorting to a mirror-projection principle to reduce the measurement time to a minimum; it is expected to provide both the bidirectional transmission (BTDF) and reflection (BRDF) functions of light-redirecting materials in a continuous way, even in presence of strong gradients in luminance; a wavelength-dependent analysis over the whole solar spectrum will also be possible, extending the materials' investigation to the thermal aspects of solar radiation. This instrument will therefore be the first of the kind allowing bidirectional functions to be assessed in both the visible and IR spectral range. This will open new perspectives in managing and controlling solar gains by adding a directional component to it and therefore bring refined design solutions to the assignment of the buildings' thermal mass. The considered samples will typically be innovative materials or coatings used for solar shading or daylight redirecting systems, as well as electric lighting components like luminaires' reflectors. An easy and cheap access to detailed light redirection data for such innovative glazing and shading systems will and therefore promote more sustainable design solutions for buildings, the lack of such data remaining one of the critical reasons why the integration of advanced fenestration systems in buildings is constrained.

The rotating support of the instrument, the heliodon, will also serve as an educational and design tool for architecture students to analyze the effect of a sun course on their scale models, and help them find solutions to improve the sunlight distribution within their building projects.

References

[1] Papamichael, K.M., Klems, J., Selkowitz, S., Determination and Application of Bidirectional Solar-Optical Properties of Fenestration Materials, Technical Report LBL-25124, Lawrence Berkeley National Laboratory, Berkeley, 1988.

[2] Apian-Bennewitz, P., Designing an apparatus for measuring bidirectional reflection/transmission, Proceedings SPIE v 2255: Optical Materials Technology for Energy Efficiency and Solar Energy Conversion, pp. 697-706, 1994.

[3] Bakker L., van Dijk, D., Measuring and processing optical transmission distribution functions of TI-materials, TNO Building and Construction Research, Delft, 1995.

[4] Breitenbach J., Rosenfeld, J.L.J., Design of a Photogoniometer to Measure Angular Dependent Optical Properties, Proceedings of International Conference on Renewable Energy Technologies in Cold Climates, pp. 386-391, Solar Energy Society of Canada, 1998.

[5] Andersen, M., Michel, L., Roecker, C., Scartezzini, J.-L., Experimental assessment of bi-directional transmission distribution functions using digital imaging techniques, Energy and Buildings 33(5): 417-431, 2001.

[6] Andersen, M., Roecker, C., Scartezzini, J.-L., Design of a time-efficient video-goniophotometer combining bidirectional functions assessment in transmission and reflection, Solar Energy Materials and Solar Cells, 88(1): 97-118, 2005.

[7] Ward, G., Measuring and modeling anisotropic reflection, ACM SIGGRAPH Computer Graphics 26(2): 265-272, 1992.

[8] Andersen, M., Rubin, M., Scartezzini, J.-L., Comparison between ray-tracing simulations and bi-directional transmission measurements on prismatic glazing, Solar Energy 74(2): 157-173, 2003.

[9] Andersen, M., Rubin, M., Powles, R., Scartezzini, J.-L., Bi-directional transmission properties of venetian blinds: experimental assessment compared to ray-tracing calculations, Solar Energy 78(2): 187-198, 2005.

[10] Ohno, Y., Hardis, J., Four-color matrix method for correction of tristimulus colorimeters, Proceedings of Imaging Science & Technology's 5th Color Imaging Conference, pp. 301–305, IS&T, 1997.

[11] Pattanaik, S., Torrance, K., Light Measurement using the Photometrics-PXL1300L CCD Camera, Technical report, Program of Computer Graphics, Cornell University, Ithaca, NY, 1998.

[12] Michel, L., Francioli, D., Meyer, J.-J., Digital image facilities for visual comfort evaluation, Proceedings Solar Energy in Buildings CISBAT 2001, pp. 205–210, Lausanne, Oct. 3-4. EPFL, 2001.

[13] Chain, C., Dumortier, D., Fontoynont, M., Consideration of daylight's colour, Energy and Buildings 33(3): 193–198, 2001.

[14] Hecht, E., Optics, Addison-Wesley Publishing Company, USA, 2nd Edition, 1987.