AN AUTOMATED DEVICE TO ASSESS LIGHT REDIRECTING PROPERTIES OF MATERIALS AND PERFORM SUN COURSE SIMULATIONS: THE HELIODOME PROJECT

Marilyne Andersen
Dean Ljubicic
Courtney Browne
Siân Kleindienst
Martin Culpepper
Massachusetts Institute of Technology
Building Technology Program, Department of Architecture
Room 5-418, 77 Massachusetts Avenue
Cambridge, MA 02139
mand@mit.edu (M. Andersen)

ABSTRACT

In this paper, the development of an original and time-efficient measurement device is proposed for the detailed investigation of the daylight distribution within buildings. It is meant to be used for two kinds of applications:

- to assess the sunlight distribution inside scale models in an automated way so as to serve as a design and educational tool for architects and students and help them find solutions to improve the sunlight distribution within their building projects.
- to achieve time-efficient bidirectional goniophotometric measurements of materials, typically used for innovative fenestration systems such as solar blinds, advanced glazing or coatings and daylight-redirecting devices, as well as energy-efficient artificial lighting components like luminaires reflectors e.g.

The functioning principle of the device in both configurations is explained here and its early stages of development are presented: design and construction of the mechanical platform, command interface prototype and characteristics of the light detection system.

1. INTRODUCTION

Beyond the obvious benefit for windows to provide a connection with the outside environment and for natural light to achieve excellent color rendering (1), numerous analyses stress the high potential of energy savings with a better integration of daylighting in a building's overall lighting management (2,3). In addition, many studies about the impact of a daylit environment on its users, typically conducted in office spaces, classrooms and retail centers, have shown that both human productivity and well-being could be significantly increased when daylight availability and access to view were enhanced (4,5,6,7,8,9). This effort in increasing the use of daylight and its control inside buildings has lead to the development of a large variety of innovative fenestration systems, including complex glazing and shading systems and devices for redirecting the direct (sun) and diffuse (sky) components of natural light (10). However, to allow the efficient integration of such daylighting systems in buildings, a detailed knowledge of the spatial distribution of emerging light for varying impinging directions is essential to accurately predict their performances for variable climatic conditions and sun courses (11, 12). The quantity used to describe these photometric properties is called Bidirectional Transmission (or Reflection) Distribution Function (BTDF, BRDF) and is illustrated in Fig. 1. This function is defined as the quotient of the luminance of a surface element in a given direction by the illuminance incident on the material (13), and hence expresses the emerging light distribution for a given incident direction. There is a strong demand for bidirectional data from manufacturers who want to develop and optimize their products, from architects to choose the appropriate system judiciously already at the project's level, and from daylighting simulation program designers to extend their potential.

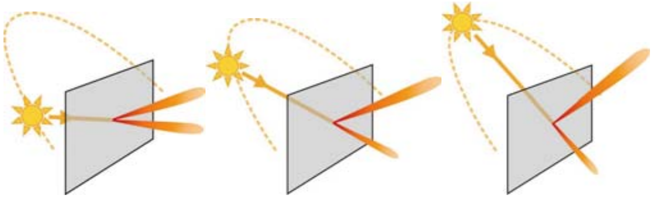


Fig. 1: Schematic representation of bidirectional functions

Securing a detailed characterization of these materials is essential to test and compare different alternatives in geometry or coatings in an objective and systematic way, and hence enhance their performance. But this assessment has to be rapid and cheap in order to be included in the systems' development process. The intuitive, but time consuming, point-by-point analyses adopted by most of the goniophotometers so far (14,15,16,17) have prevented extensive BTDF or BRDF databases to be available for manufacturers. The video-goniophotometer recently developed at the Solar Energy and Building Physics Laboratory (LESO-PB) at the Swiss Federal Institute of Technology (EPFL) (18,19) successfully answered this need by allowing a much higher time-efficiency in characterizing whole window systems.

The instrument presented here also relies on digital imaging techniques for time-efficiency, but resorts to a mirror-projection principle similar to the one described in (20), so as to reduce the measurement time even further than EPFL's device. Like the latter, it is expected to provide both the BTDF and BRDF of the considered materials in a contiuous way, even for samples showing strong gradients in luminance. But on top of these capabilities, a wavelength-dependent investigation over the whole solar spectrum will also be possible. The samples will typically be innovative materials or coatings used for solar shading or daylight redirecting systems, or of electric lighting components like luminaires' reflectors. Its rotating support, 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 in their building projects (see Fig. 2).

Fig. 2: Study of sunlight penetration inside a scale model

2. MECHANICAL DESIGN

The design of the platform has to fulfill an extensive list of geometric, structural and flexibility requirements because of its dual application as a support for scale models and as the rotational basis for bidirectional measurements of samples.

2.1 Aims and constraints

The light source remaining fixed, the platform must be able to perform computer-driven rotational movements around two perpendicular axes (see Fig. 3): horizontal axis for altitude (tilt), normal axis for azimuth, both within a 360° range (1 complete tour). In addition, the following constraints apply:

- 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 be a disk of 1.5 m diameter, providing 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 conversion from scale model mode to BT(R)DF mode must be as easy as possible;
- obstruction to both incoming and emerging light flux must be minimized on both sides of the platform.

The final design, schematized in Fig. 3, meets all of these requirements. The main components and sample holding system are described in the following sections.

2.2 Main structural components

Two major structural elements make up the heliodome's platform: an octagonal frame rotating around the horizontal axis and the 1.5 m diameter disk, supported by the former. The octagonal frame is made of 8 identical hollow aluminum tubes of square section, welded together, as illustrated in Fig. 4(d).

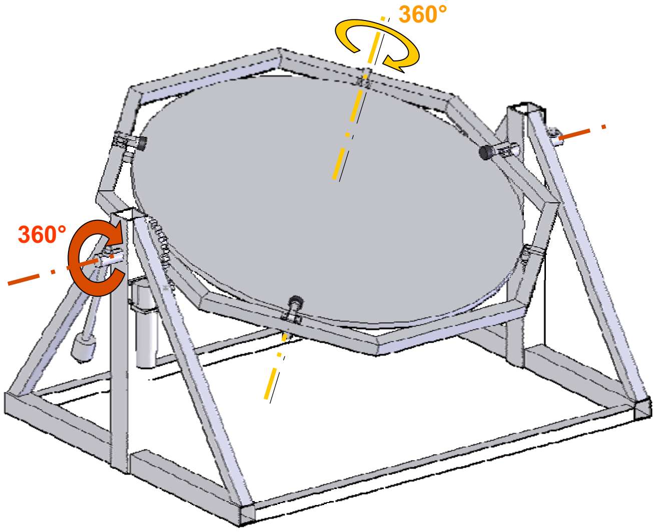


Fig. 3: Design concept of the table with two rotation axes

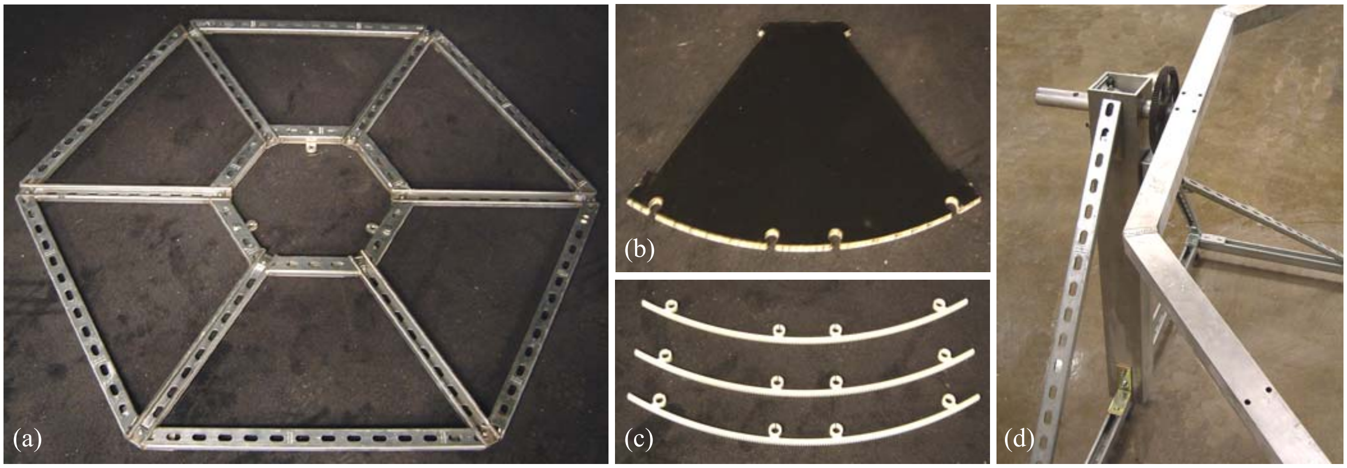


Fig. 4: Main components of supporting platform: (a) structural hexagon (b) trapezoidal honeycomb pieces (c) gears for azimuth rotation (d) gears and octagonal frame for altitude rotation

The disk is carried by the octagonal frame by three sets of rollers (illustrated in Fig. 3), its rotation being driven by peripheral gears (see Fig. 4(c)).
The disk consists of an assembly of a hexagonal frame made out of Unistrut® rails (see Fig. 4(a)) and of a set of 6 curved trapezoidal pieces of aluminum honeycomb (see Fig. 4(b)). The specific section profile of Unistrut® ("U" ending with cuffs towards the interior) makes it possible to slide fixing devices (clips) for holding the scale model's base; this railing system was assembled with bolts and thereafter stiffened with additional welding so as to reduce its bending to a negligible level. Samples are to be fixed inside its open center (see Section 2.3).
Waterjetting techniques were used to produce the aluminum honeycomb pieces and the gears with a 1/10 mm accuracy. The honeycomb structure allows it to show high stiffness combined with low weight; the gears are made out of Nylon. To attach them together, a "jigsaw-puzzle" pattern was designed, to insert the protruding parts of the gears into the fitting holes of the honeycomb (see Figs. 4(b) and 4(c)).

The spur gears responsible for the azimuth rotation of the disk are fixed on the octagonal frame. Four pairs of rollers are mounted on the top and bottom of the frame, each of them presenting a square cantilever to facilitate mounting. They include roller ball bearings to center the disk in the plane of the octagonal frame.
As the table's design incorporated heavy torque loads, a counterweight system was added, illustrated in Fig. 3.

2.3 Sample holder for goniophotometric measurements

The device accommodates samples whose dimensions are between 50mm and 200 mm in diameter (or in diagonal dimension), with thicknesses less than 20 mm. The sample holder consists of a pair of diaphragms of various aperture diameters (10, 20, 50, 100 and 150 mm) to cope with the range of possible sample sizes. They hold the sample in place by compression ("sandwich" system; a sticky coating will be added to prevent the sample from sliding) thanks to three springs of adjustable height. These springs are inserted into bolts fixed to the central part of the Unistrut® frame (see Fig. 4(a)). 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. To be able to change the sample and the thin diaphragms from the same side, the latter are carved to accomodate the spring bolts, while the reinforcing one on the other side remains in place.

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.

3. ROTATIONAL MOVEMENTS

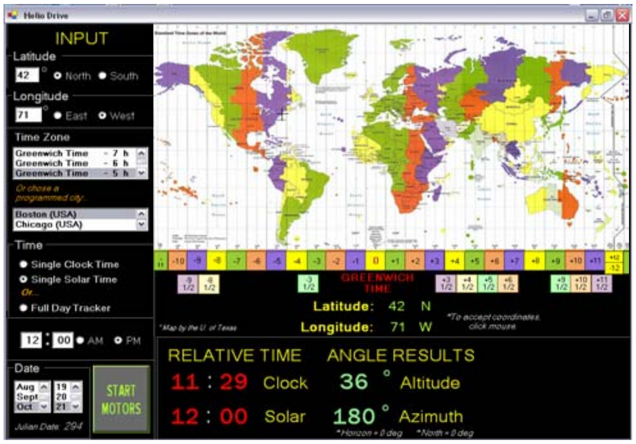
In either configuration, varying incident beam directions must be simulated: over a sun course for scale model measurements and to generate a BT(R)DF database for the goniophotometric application.

The movements of the platform are computer-driven by a graphical interface developed in Visual Basic (Visual Studio.NET), whose current configuration is shown on Fig. 5. Control is achieved by a microcontroller. Movements are determined by the sun's elevation and azimuth angles corresponding to the specified parameters of time, date, location, given by Equation (1):

$$\sin(\eta) = \sin(\Lambda)\sin(\delta) + \cos(\Lambda)\cos(\delta)\cos(\zeta)$$
$$\sin(\phi) = \sin(\zeta)\cos(\delta) / \cos(\eta) \qquad (1)$$

where η is the elevation angle from the horizon, ϕ is the azimuth angle from North (going East), Λ is the latitude, δ is the sun's declination angle, and ζ is the hour angle from Greenwich.

Once they are converted into parameters relevant to the platform's motion, also accounting for the building's orienttation, the target number of motor encoder pulses are calculated and fed to the motor controllers through two serial ports. Each motor's speed is controlled via a 0 to 5V pulse width modified (PWM) square waves, whose duty cycle is manipulated by the motor controller, programmed in C.


Helio Drive

INPUT

Latitude
42 ° ○ North ● South

Longitude
71 ° ● East ○ West

Time Zone
Greenwich Time - 7 h
Greenwich Time - 6 h
Greenwich Time - 5 h

Or chose a programmed city...
Boston (USA)
Chicago (USA)

Time
● Single Clock Time
○ Single Solar Time
Or...
● Full Day Tracker

12 : 00 ● AM ○ PM

Date
Aug / Sept / Oct — 19 / 20 / 21
Julian Date 294

START MOTORS

Latitude: 42 N
Longitude: 71 W
*To accept coordinates, click mouse

RELATIVE TIME
11 : 29 Clock
12 : 00 Solar

ANGLE RESULTS
36 ° Altitude
180 ° Azimuth
*Horizon = 0 deg *North = 0 deg

Fig. 5: Command interface prototype

4. LIGHT DETECTION SYSTEM

When analyzing the light distribution inside a scale model, usually from a qualitative point of view only, various detection instruments can be used, such as a still camera, a video-camera or the human eye.

For goniophotometric measurements, the light detection system is more elaborate, as illustrated in Fig. 6. The light flux received by the sample from the source is reemitted (after either reflection or transmission) towards the interior (mirror) side of a half-silvered 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, imagined by Ward in 1992 for image rendering applications (20), allows the complete emerging light distribution to be captured in a single image. For BTDF measurements, the Heliodome is turned upside down from its configuration in Fig. 6, which means that the camera is obstructing the incident light for a small range of azimuth angles. For the few cases where the sample's heterogeneity makes this critical, it can be rotated 90° on its holder to fully characterize it within the missing angular range.

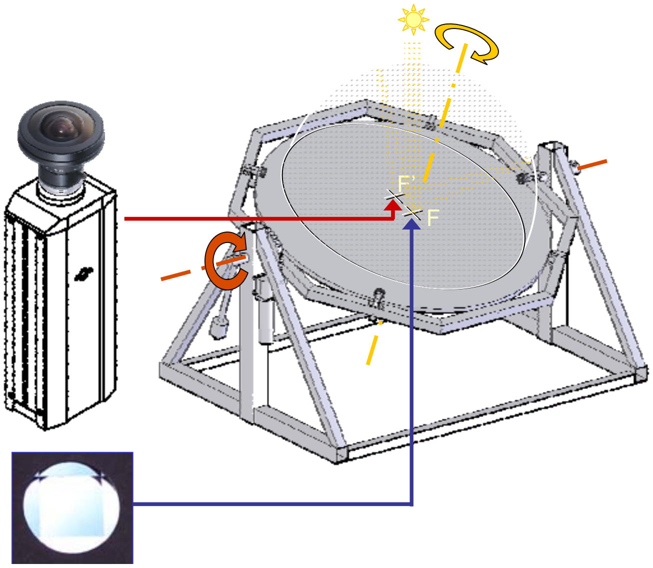


Fig. 6: Conceptual sketch of the video-goniophotometer

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 (1.5 m in diameter), the collimation is not as critical because the light distribution assessment is mainly qualitative; attaining sharp shadows is sufficient.

4.1 Light sources as "artificial suns"

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 Molebeam 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 Fig. 7. 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 (21) and an optimization calculation made in Microsoft Excel® accommodating the constraints imposed by the dimensions of the black room and its cumbersome ceiling fixtures.

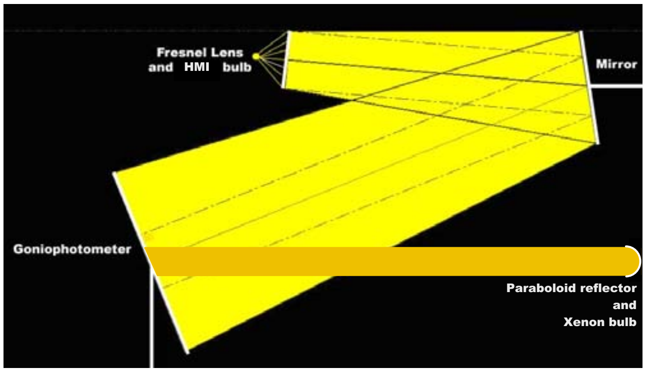


Fig. 7: Light beam adjustments in both configurations

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 Fig. 7).

4.2 Ellipsoid for emerging light collection

The hemi-ellipsoidal shell used for goniophotometric measurements must be semi-transparent (silvered on the inside only) so as to let the beam coming directly from the light source reach the sample, even in reflection mode (see Fig. 6). 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 allows the whole emerging space to be investigated within a single image capture.
The camera is used as a luminance-meter and must be calibrated accordingly, including the identification of emerging directions as image pixels.

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, illustrated on Fig. 8.

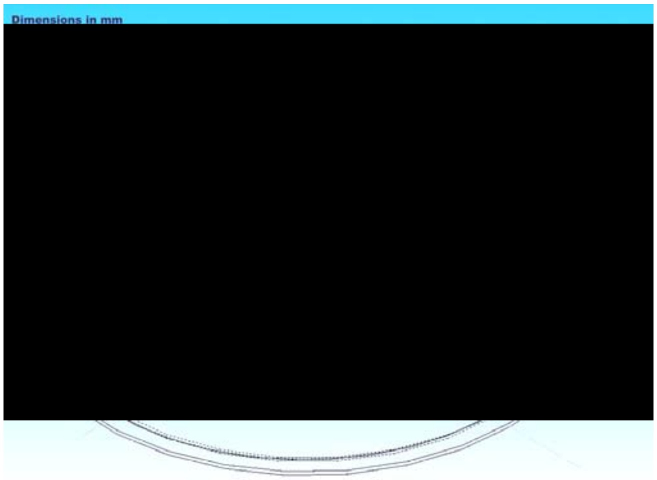


Fig. 8: Sketch and dimensions of the ellipsoid

4.3 Video-detection over visible and near-IR ranges

To cover the visible range, the computer-commanded, digital color camera Kappa® DX 20 N (CCD sensor: ½'', 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'.
When capturing images inside scale models, it can be equipped with an endoscopic lens instead, of diameter 10 mm and length 450 mm. This 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 replaced by the fish-eye lens.

As CCD sensors are only sensitive up to 1100 nm, a second camera is needed to cover the IR range up to about 2200 nm for goniophotometric measurements. The IR camera model used for preliminary tests is the DAGE-MTI NC-68DX camera, described as covering wavelengths up to 2200 nm, but we expect this specification to be too optimistic. New research will be needed for its calibration method.

5. CONCLUSION

The functioning principle and early development stages of the "Heliodome" are presented in this paper. This device is capable of both assessing sunlight penetration inside scale models and of performing video-based bidirectional goniophotometric measurements on materials and coatings, in either transmission (BTDF) or reflection (BRDF) modes. Digital imaging techniques will be used for light detection in both configurations, the spectral range being extended to the near IR for goniophotometric applications. 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.

Today, no experimental equipment suitable for daylighting applications is capable of answering requirements both in time-efficiency and completeness of information (transmission, reflection, spectral investigation), which places this research in a leading position. It is expected to be complemented by ray-tracing simulations for the characterization 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. Having an easy and cheap access to detailed light redirection data for innovative glazing and shading systems will help manufacturers in increasing the performances of their products, and architects in choosing them judiciously; it will also allow a reliable modeling of light propagation in rooms using advanced fenestration systems.

6. ACKNOWLEDGMENTS

The authors were supported by the Massachusetts Institute of Technology.

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