THE HELIODOME PROJECT: AN INNOVATIVE APPROACH IN ASSESSING SOLAR-OPTICAL PROPERTIES OF LIGHT-REDIRECTING MATERIALS IN COMBINATION WITH SUN COURSE SIMULATIONS

M. Andersen; N. Gayeski; E. Stokes; R. Osser; C. Browne

Building Technology Program, Dept of Architecture, Massachusetts Institute of Technology, MIT Room 5-418, 77 Massachusetts Ave, Cambridge MA 02139, USA. Email: mand@mit.edu

ABSTRACT

The Heliodome is a new type of video-based goniophotometer to measure materials and coatings intended to be used for advanced fenestration technologies or energy-efficient luminaires. Using calibrated digital cameras combined with a light projecting surface (ellipsoidal mirror), the spectral, bi-directional transmission or reflection properties of these materials can be assessed to a reasonable degree of accuracy. Its major innovations compared to other devices are to enable an analysis of both the visible and the near-infrared portions of the solar spectrum, to provide spectral as well as photometric light distribution data, and to ensure a continuous investigation of the transmitted or reflected light in a time-efficient way.

The rotating table also serves as a heliodon, an architectural design tool for visualizing sunlight distribution inside a scale model and performing analyses on appropriate sun control strategies. This automated setup is complemented by a portable, manual outdoor heliodon that uses the real sky and sun as light sources.

The paper details current progress in the development of this dual use device, called the “Heliodome”, that includes an original methodology for using a Charge Coupled Device (CCD) camera and a near-infrared Indium Gallium Arsenide (InGaAs) camera to measure arbitrary spectra.

INTRODUCTION

The benefits of good daylighting in buildings range from aesthetically pleasing spaces to a significant reduction in energy consumption and often include improved visual comfort or even sense of well-being [1-2]. The last half century saw a generation of improvements in fenestration system technologies to increase the energy performance and comfort of buildings. To achieve these goals and prevent discomfort, glare and overheating issues, advances have been made in angularly and spectrally selective fenestration systems to refine the control of how much and which part of the solar spectrum is transmitted or reflected into (or rejected from) a building under different seasonal and climatic conditions.

Optimizing the way visible light and near-infrared solar radiation penetrates a building and is distributed inside has great potential for increasing useful daylight and reducing thermal loads and recent efforts have been made to develop an always growing variety of daylighting technologies and façade systems to take advantage of these effects [3-5]. Light-redirecting systems are however difficult to describe both because of their complex optical properties and the many parameters involved: climatic, diurnal and latitudinal variations in incident illumination, angular dependency of the emerging light distribution, and relationship between fenestration system and illuminated space. These systems are usually both spectrally and angularly selective. It is therefore important to describe how solar radiation will be transmitted and/or reflected by them, in terms of energy, direction and spectrum.

The quantities used to describe these properties are spectral (wavelength-dependent) Bidirectional Transmission or Reflection Distribution Functions (BTDFs or BRDFs, also more generally called BSDFs for Scattering Functions) [6], which can be experimentally assessed with goniospectrometers.

Existing goniophotometers (measuring photometric BTDF and/or BRDF values over the visible range i.e. that account for the human eye's sensitivity to colors and do not offer any spectral information) already exist and rely on a variety of approaches, mostly based on the scanning of all the emerging directions of light [7]. Only two devices, also based on scanning methods, allow fenestration systems to be characterized spectrally, described in [8] and [9], with a possibility to extend the wavelength to NIR for the latter. Because scanning cannot avoid the risk of missing transmission or reflection features between measured points, this approach often requires refinements in resolution for high light gradients and can thus become a time-consuming process. Projection-based approaches, relying on calibrated digital cameras, have been developed as alternatives [10-11] but have not so far covered wavelength ranges beyond the visible or even been able to provide spectral analysis capabilities.

A VIDEO-BASED GONIOPHOTOMETER FOR SPECTRAL ANALYSES

This paper describes an innovative approach in characterizing the optical properties of new fenestration systems and technologies, and thus in predicting their performance in terms of lighting and solar gains management potential. The device, a new type of video-based goniophotometer, will assess quasi-spectral radiometric BSDFs of materials and coatings used for complex fenestration systems (CFS) such as light-redirecting glazing, interior or exterior shading, film coatings and reflectors. It will be able to provide both photometric and radiometric, wavelength-dependent BSDFs over most of the solar spectrum (400 to 1700 nm).

Principle

Its functioning principle, illustrated in Figure 1(a), relies on the use of calibrated digital cameras sensitive to the visible and the near-infrared ranges of the solar spectrum and on collecting the light emerging from the sample on an ellipsoidal mirror before it is detected by the camera, both being supported by a motorized rotating table and illuminated by a fixed light source. The camera and the sample are placed at the two foci of the hemi-ellipsoid, which is a semi-transparent acrylic shell coated with aluminium, shown on Figure 1(b). One of the ellipsoid's foci is the centre of the rotating table itself.

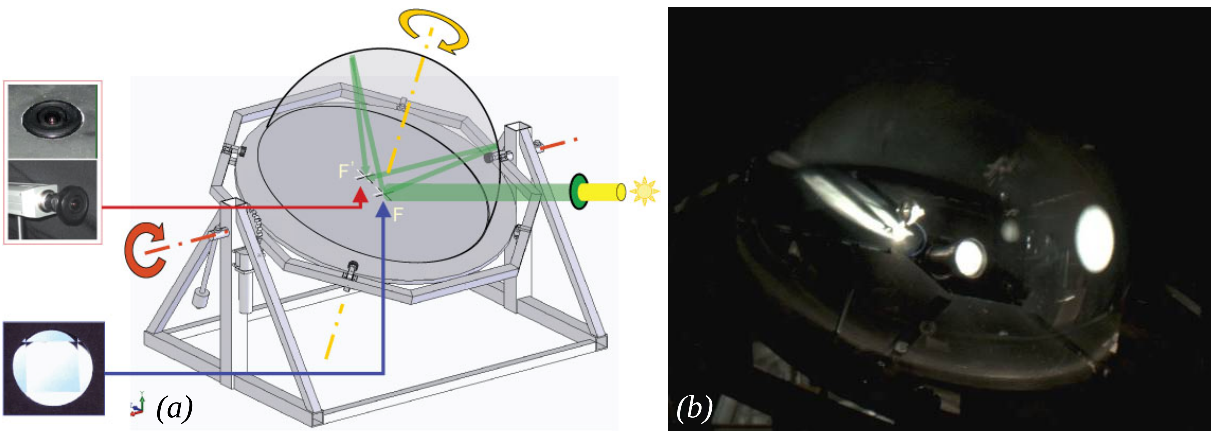


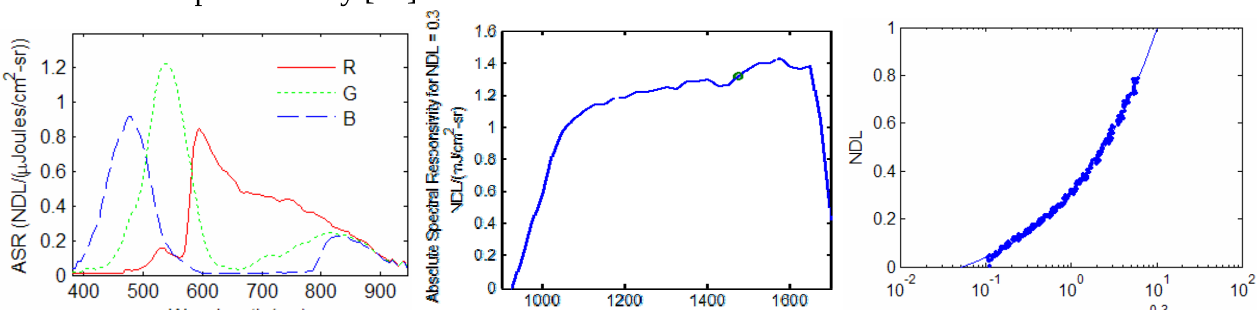
Figure 1: The Heliodome project. (a) Functioning principle: light emerging from the sample (focus F) is detected by a digital camera equipped with a fish-eye lens (focus F') and incoming light is filtered to as to enable a spectral analysis of the material. (b) Reflection of light on the actual semi-transparent ellipsoid mirror when fixed on the rotating platform.

Digital cameras as multiple points radio- and luminance-meters

Two kinds of digital cameras are used: a Charge Coupled Device (CCD) camera to cover the visible wavelength range, and an Indium Gallium Arsenide (InGaAs) camera for the near-infrared (up to 1700 nm). Both are equipped with a fish-eye lens to visualize the entire hemi-ellipsoid from the inside (180 degree opening angle).

For each incident direction, a set of images are to be taken at various exposure times and be converted into radiance maps so as to produce a High-Dynamic Range (HDR) image of the interior of the ellipsoid. To convert the raw image information, i.e. its pixels' digital levels (R, G and B channels for the CCD camera, unique channel for the InGaAs camera), into radiance values, a set of spectroradiometric calibration procedures have to be applied first, and incoming light filtered into smaller wavelength intervals so as to extract spectral information from the images, as explained below [12]. Pixel coordinates on the images are then related to directions along which light emerges from the sample, a relationship that depends on the geometry of the ellipsoid and the optical properties of the fish-eye lens. From the irradiance at the sample plane and accounting for the fact that light is first reflected on the ellipsoid's surface before being detected by the camera, spectral BSDFs can be deduced from the wavelength-dependent radiance matrices based on the HDR images.

The spectral sensitivity of both cameras is described by the relationship between the digital response of each channel and the corresponding radiance value (directly related to the spectral exposure of the pixel's sensor area), as a function of wavelength and integration time (see Figure 2). This relationship was determined by comparing camera output to known monochromatic radiances for various integration times, using a calibrated light source, a monochromator, a reflectance standard and a reference spectrometer (calibrated integrating sphere used in combination with a silicon-based spectrometer). For polychromatic radiation such as natural daylight, the absolute responsivity of the camera are weighted sums of the ASRs, the weights being determined by the relative spectrum of detected light, which was confirmed experimentally [12].



(a) *(b)* *(c)*

Figure 2: Spectroradiometric calibrations. (a) Absolute Spectral Responsivity of CCD camera at each wavelength. (b) ASR of InGaAs camera. (c) Logistic dose response function fit to the normalized digital responses of R, G and B channels for any wavelength.

If the relative spectrum of the detected light is known, such as for a white wall illuminated by daylight after transmission through a clear pane of glass or when analyzing the optical properties of spectrally neutral samples, these spectroradiometric calibrations already allow the use of these digital cameras as extremely time-efficient, multiple points luminance- and radiometers. But in many instances, the relative spectrum of detected light will be unknown, which is typically the case for any spectrally-selective material whose transmission and reflection properties are yet to be determined. In this case, a filtering system of detected (or incoming) light has to be implemented so as to split the unknown spectrum into wavelength intervals across which the above-described calibration procedures enable an accurate estimation of the total radiance, i.e. over which the camera sensitivity is flat enough.

Simulations were carried out to determine what errors on predicted radiances could be expected depending on the wavelength intervals chosen, using filters available on the market [12]. From this study, a set of eight Schott Color Glass filters were selected (Figure 3), whose combination enabled the best compromise between limiting the number of filters (and hence number of actions to perform during BSDF measurements) and ensuring reasonable accuracy.

Extracting spectral information from digital levels

For any spectrally-selective sample whose optical properties are not yet known, incoming light is filtered into smaller wavelength intervals (Figures 3(a,b)), and images captured for each of these intervals (nine altogether accounting for the NIR range which remains unfiltered because of its relatively flat sensitivity, see Figure 2(b)). The response of the camera to detected light depends on the sample's optical properties but also on the incident beam, the filters' and the ellipsoid's optical properties. Since these can all be determined through appropriate measurements and remain unchanged (heterogeneities and imperfections in the ellipsoid's coating or geometry can be assessed and accounted for [12]), the only unknown is the sample's bidirectional spectral reflection or transmission coefficients, to be determined along each emerging direction (or for each pixel on the image) and for each incident direction.

As a first step, it is assumed that the sample is neutral across each wavelength interval, which leads to an estimate of the total radiance transmitted or reflected in every direction within each wavelength interval, based on the calibrations and calculation procedures described above [12]. As can be observed on Figure 3(c), this assumption still enables a fair description of the spectral properties of materials according to step curve, with errors on radiance estimation within each interval remaining below 5% for most spectra (the final error on estimated BSDFs will probably be higher, but has not yet been evaluated).

Once images have been captured for each of these filters and the radiance across each corresponding wavelength interval estimated, total radiometric and photometric BSDF values over the whole visible and near-infrared ranges can be calculated reliably (relative errors for typical samples were lower than 3%) [12]. Refinements in estimating the spectral properties of the sample are then applied, based on an optimization method still under development.

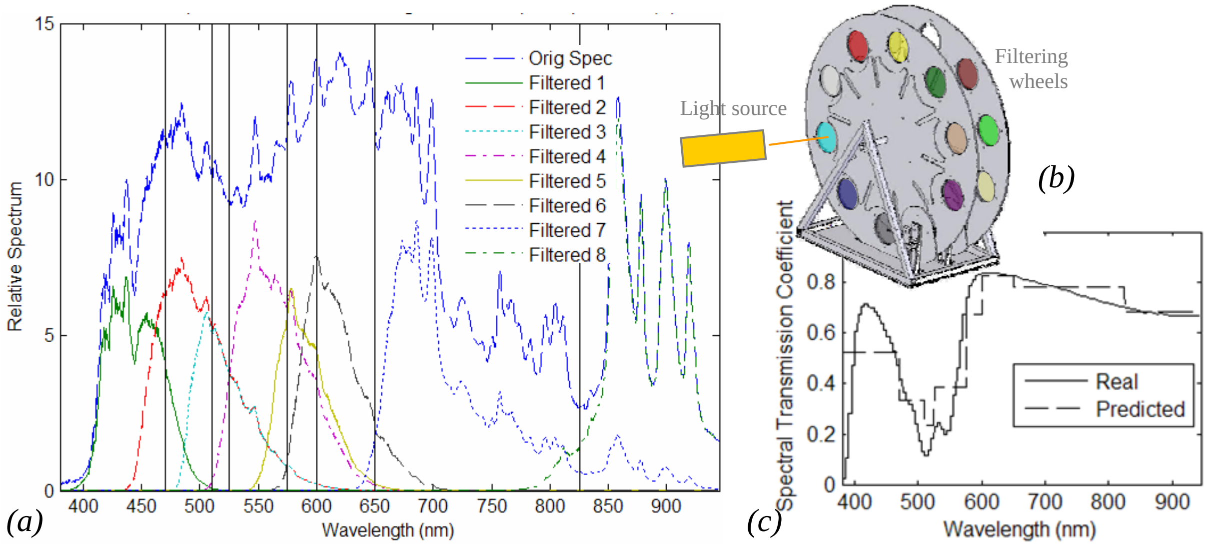


Figure 3: Quasi-spectral analysis of materials. (a) Spectra of incoming filtered light with associated wavelength intervals limits. (b) Design of the filtering system. (c) Predicted quasi-spectral BTDFs compared to a transmission real spectrum, in one emerging direction.

HELIODON APPLICATIONS

To study a scale model's response to the very variable nature of sunlight, sun course simulators (heliodons), generally consisting of a supporting platform and a light source, can be used by either rotating the source around the scale model's centre or rotating the scale model itself to reproduce a specific sun course pattern depending on the location and the time of the day. Two approaches have been designed at MIT and are described below, one of which uses the rotating platform of the Heliodome as its base.

Automated Heliodon

The automated Heliodon consists of a computer-controlled rotating platform, a fixed light source and an interface for digital image capture and can reproduce any sun angle or sequence of sun angles (over the course of a day e.g.) at any given location. Before it reaches the scale model, light is first bounced off of a mirror so as to accommodate space constraints and the large illuminated area needed while still keeping a small beam spread to get sharp shadows.

To visualize the effects of sunlight penetration on scale models, a CCD camera can be used and secured anywhere on the table with a flexible arm. A wide-angle lens, a fish-eye lens or an endoscopic lens (see Figure 4(a)) can be chosen depending on the desired kind of analysis.

The interface allows the user to choose the location, times and dates that are to be investigated and visualize sunlight penetration in real time. The captured images can then be viewed in matrices or as fake videos [13]. Careful analyses of the images enable the user to point out potential glare risks, strong contrasts and predict probable overheating problems. Several shading strategies, window design options and daylighting systems can thus be tested and compared and informed decisions made about the best design choices.

Portable Heliodon

The portable Heliodon (Figure 4(b)) is a design and educational tool for sunlight and daylight penetration studies outdoors, also using scale models. The model is fixed on a small table that has three degrees of freedom. A set of sun dials is used to manually orient the model so as to reproduce specific conditions in the intended building location. Under cloudy conditions, a set of stereographic sun charts are used to calculate the appropriate tilting angles of the table (depending on the current and desired location and the current and desired times and dates).

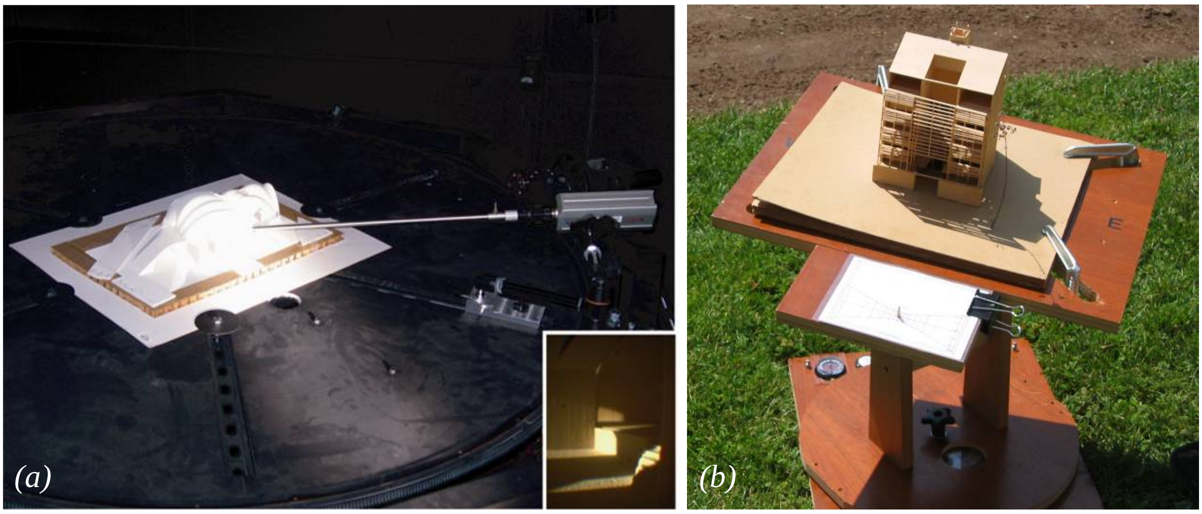


Figure 4: The two versions of a Heliodon developed at MIT. (a) Automated approach with a computer interface for efficient image capture in sequences (here shown with endoscopic lens and resulting interior view). (b) Manual approach for outdoor testing using sundials.

As a complement to previous studies on the accuracy of scale model measurements [14-15], a Radiance-based analysis was conducted to evaluate the most critical parameters in ensuring reliable experimental conditions such as current and desired sun position, sky conditions, surrounding obstructions and ground reflectance [13]. Although model tilting or high surrounding obstacles were expected to be major error sources because of sky vault misrepresentation, solar altitude was revealed as the most important parameter, outlining the importance of conducting these experiments at times where current and desired sun altitudes matching closely: these have to differ by less than 10 or 20 degrees if illuminance measurements are to be reliable within a 5% relative error whereas even large variations in sky conditions, ground reflectance and surroundings usually induced lower errors.

CONCLUSION AND OUTLOOK

This paper described the main achievements of the Heliodome project so far, including a novel approach in extracting quasi-spectral information from digital images, a high-precision, computation-based calibration of CCD and InGaAs cameras and innovative ways to use known information about the sun course to inform design with quick-learning tools. Other issues such as the ellipsoid characterization and spectrum estimate optimization are still under development.

The use of these calibrated cameras and an appropriately filtered light source will enable reasonably accurate, angularly-dependent measurement of spectral radiance and luminance of the light flux emerging from the considered material or coating over more of the solar spectrum than previously possible. There is a growing interest shown by practitioners, the window components industry and designers of energy and lighting simulation tools in this kind of data, which shows a high potential for this measurement device to fit their needs and help better optimize the use of solar radiation for lighting and thermal performance.

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